Profiles of Operational and Research Forecasting of Smoke and Air Quality Around the World

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Abstract

Biomass burning has shaped many of the ecosystems of the planet and for millennia humans have used it as a tool to manage the environment. When widespread fires occur, the health and daily lives of millions of people can be affected by the smoke, often at unhealthy to hazardous levels leading to a range of short-term and long-term health consequences such as respiratory issues, cardiovascular issues, and mortality. It is critical to adequately represent and include smoke and its consequences in atmospheric modeling systems to meet needs such as addressing the global climate carbon budget and informing and protecting the public during smoke episodes. Many scientific and technical challenges are associated with modeling the complex phenomenon of smoke. Variability in fire emissions estimates has an order of magnitude level of uncertainty, depending upon vegetation type, natural fuel heterogeneity, and fuel combustion processes. Quantifying fire emissions also vary from ground/vegetation-based methods to those based on remotely sensed fire radiative power data. These emission estimates are input into dispersion and air quality modeling systems, where their vertical allocation associated with plume rise, and temporal release parameterizations influence transport patterns, and, in turn affect chemical transformation and interaction with other sources. These processes lend another order of magnitude of variability to the downwind estimates of trace gases and aerosol concentrations. This chapter profiles many of the global and regional smoke prediction systems currently operational or quasi-operational in real time or near-real time. It is not an exhaustive list of systems, but rather is a profile of many of the systems in use to give examples of the creativity and complexity needed to simulate the phenomenon of smoke. This chapter, and the systems described, reflect the needs of different agencies and regions, where the various systems are tailored to the best available science to address challenges of a region. Smoke forecasting requirements range from warning and informing the public about potential smoke impacts to planning burn activities for hazard reduction or resource benefit. Different agencies also have different mandates, and the lines blur between the missions of quasi-operational organizations (e.g. research institutions) and agencies with operational mandates. The global smoke prediction systems are advanced, and many are self-organizing into a powerful ensemble, as discussed in section 2. Regional and national systems are being developed independently and are discussed in sections 3-5 for Europe (11 systems), North America (7 systems), and Australia (3 systems). Finally, the World Meteorological Organization (WMO) effort (section 6) is bringing together global and regional systems and building the Vegetation Fire and Smoke Pollution Advisory and Assessment Systems (VFSP-WAS) to support countries with smoke issues and who lack resources.

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1. Introduction

Biomass burning has shaped many of the ecosystems of the planet (Bowman et al., 2009), and for millennia humans have used it as a tool to manage the environment (Pyne, 2001). When widespread fires occur, the health and daily lives of millions of people can be affected by the smoke, often at unhealthy to hazardous levels (Jaffe et al., 2020) leading to a range of health consequences such as respiratory issues (Alman et al., 2016a; Henderson & Johnston, 2012; Lipner et al., 2019; Rappold et al., 2012), cardiovascular issues (H. Chen et al., 2021; Gan et al., 2017; Wettstein et al., 2018), and mortality (Doubleday et al., 2020; Johnston et al., 2012; C. E. Reid et al., 2016; Xi et al., 2020). It is critical to adequately describe and include smoke and its consequences in atmospheric modeling systems to meet needs such as addressing the global climate carbon budget and informing and protecting the public during smoke episodes.

Biomass burning is highly episodic, with great variability from day to day and year to year, making it extremely difficult to parameterize and simulate. Smoke plumes can linger close to the ground where people breathe and also be lofted high into the atmosphere, transporting long distances. Further, fire interacts with the atmosphere, creating its own fire weather, such as smoke-induced density currents (Clements et al., 2018) and pyrocumulonimbus clouds (Peterson et al., 2017). On regional to global scales, smoke interacts with the atmosphere, changing the radiative budget of the atmosphere, modifying winds and temperature, and interacting with cloud processes (Grell et al., 2011). Within the smoke plume, the rich mixture of trace gases and aerosols continues to transform through a variety of chemical and physical processes (Akagi et al., 2011; Crutzen & Andreae, 1990; Hatch et al., 2017; Hodshire et al., 2019).

Previous chapters of this book outline the scientific and technical challenges associated with modeling the complex phenomenon of smoke. Variability in fire emissions estimates has an order of magnitude level of uncertainty, depending upon vegetation type, natural fuel heterogeneity across the landscape, and fuel combustion processes (French, 2023; Prichard, 2023). These emission estimates are input into dispersion and air quality modeling systems, where their vertical allocation and temporal release, transport patterns, and chemical transformation and interaction with other sources lends another order of magnitude of variability to downwind estimates of trace gases and aerosol concentrations (Mallia, 2022). Forecasting systems have a particularly challenging task because they need to make more assumptions than do retrospective modeling studies. Forecasting systems do not have a priori information about fire locations, fire behavior, timing of emissions, or how high emissions are lofted and distributed vertically in the atmosphere. Instead, they make assumptions, such as persistence, where the fire information from yesterday is assumed to apply to every future day in the forecast time period. Coupled atmosphere-fire behavior systems (Coen et al., 2013; Linn et al., 2002; Mandel et al., 2014; Mell et al., 2007), are promising as they can track the evolution of ongoing fires but as yet are too computationally intensive to implement on regional and global scales. Data assimilation techniques combine numerical model predictions with observational datasets to provide a powerful means of initializing model runs to address some of these forecasting challenges (Hyer et al., 2023).

Here we merge the science and data of the previous chapters into smoke prediction systems that operate at global, regional, and local scales to simulate smoke impacts. This chapter profiles many of the global and regional smoke prediction systems currently operational or quasi-operational in real time or near-real time. It is not an exhaustive list of systems, but rather is a profile of many of the systems in use to give examples of the creativity and complexity needed to model the phenomenon of smoke. This chapter, and the systems described, reflect the different needs of agencies and regions, where the various systems are tailored to the best available science for a region and the specific challenges of the region. Smoke forecasting needs range from warning and informing the public about potential smoke impacts to planning burn activities for hazard reduction or resource benefit. Different agencies also have different mandates, and the lines blur between the missions of quasi-operational organizations (e.g. research institutions) and agencies with operational mandates.

The global smoke prediction systems are advanced and many are self-organizing into a powerful ensemble, as discussed in section 2. Regional and national systems are being developed independently and are discussed in sections 3-5 for Europe (11 systems), North America (7 systems), and Australia (3 systems). Finally, the World Meteorological Organization (WMO) effort (section 6) is bringing together global and regional systems to form an ensemble to support countries with smoke issues and who lack resources. For each system we discuss how fire activity information is obtained, how fire emissions are calculated, and how atmospheric transport and chemical transformation (if included) of the smoke plume is treated.

2. Global Systems and the International Cooperative for Aerosol Prediction (ICAP)

The International Cooperative for Aerosol Prediction (ICAP) community is a grassroots organization founded in 2010 by developers from major operational and research centers. The mission of ICAP is to promote community development of global aerosol observations, data assimilation, and prediction technologies that can support operational aerosol forecasting (Benedetti et al., 2011; Colarco et al., 2014; J. S. Reid et al., 2011). The core participants in the ICAP model have grown from the original five to the current nine operational/research centers. One of ICAP's most significant contributions to the community is the development of the ICAP-Multi Model Ensemble (ICAP-MME; Sessions et al., 2015; Xian et al., 2019), a global multi-model aerosol forecasting ensemble consensus for basic research and the baselining of operational products. The ICAP-MME provides a testbed of probabilistic aerosol forecasts, helps to identify challenging areas for aerosol modeling, and forges valuable collaborations among forecast centers.

2.1. Participating centers and core models

As of June 2021, the ICAP modeling system includes nine operational or quasi-operational global aerosol forecast models maintained by major numerical weather prediction (NWP) or research centers from North America, Europe, and Asia. These models include the following eight comprehensive global aerosol models and one dust-only model (Table 1):

- European Center for Medium-Range Weather Forecasts-Copernicus Atmosphere Monitoring Service (CAMS; Rémy et al., 2019)
- Fleet Numerical Meteorology and Oceanography Center (FNMOC)/Naval Research Laboratory (NRL)-Navy Aerosol Analysis and Prediction System (NAAPS; Lynch et al., 2016)
- Japan Meteorological Agency (JMA)-Model of Aerosol Species in the Global Atmosphere (MASINGAR; Tanaka & Ogi, 2018)
- NASA Global Modeling and Assimilation Office (GMAO) Goddard Earth Observing System (GEOS; Colarco et al., 2010)
- NOAA Global Ensemble Forecast System (GEFS) –Aerosols (Zhang, et al., to be submitted)
- Barcelona Supercomputing Center (BSC) Multiscale Online Nonhydrostatic AtmospheRe CHemistry model (MONARCH; Badia et al., 2017; Klose et al., 2021)
- Météo France Modèle de Chimie Atmospherique à Grande Echelle (MOCAGE; Guth et al., 2016);
- Finnish Meteorological Institute (FMI) System for Integrated modeling of Atmospheric coMposition (SILAM; Sofiev et al., 2015)
- UK Met Office (UKMO) dust model (Johnson et al., 2011)

2.2 Variations in model configuration

The ICAP models are driven mostly by independent operational/quasi-operational meteorological models developed at each NWP/research center. Aerosol variables are either computed concurrently with the meteorological fields (“inline”) or are run in separate calculations forced by stored NWP fields (“offline”). Depending on the resolution of the underlying meteorology, the aerosol models have different horizontal and vertical resolutions, ranging from 0.1° x 0.1° latitude/longitude and 137 vertical layers to 1.0° x 1.0° and 40 layers; in several cases the aerosol forecast is run at a coarser resolution than the operational NWP model. The comprehensive models carry a full set of aerosol species normally considered in operational models, including dust, sea salt, biomass burning (BB) smoke (combined black carbon and particulate organic matter-POM from some models) and varying forms of pollution aerosols (sulfate, possible nitrates, and anthropogenic organic aerosols). All of the ICAP models simulate the full aerosol life cycle, including sources, sinks, microphysics, chemistry, and transport, which make them different from tracer models. The treatment of these aerosol processes differs considerably between models, with only a few shared components (see below and Table 1).

2.3 Biomass burning aerosol species and emission sources

BB smoke particles can dramatically affect regional total aerosol distributions, significantly affecting energy balance and air quality. To account for their ever-changing impact, dynamic smoke sources are included in nearly all operational global aerosol models. Black carbon (BC) and organic carbon (OC) are the two major particle components of BB smoke. Because of their drastically different optical properties, many models carry BC and OC as separate aerosol species, and smoke resulting from BC and OC are often combined with those emitted from anthropogenic pollution sources because of the computational burden of extra aerosol types. Only two current ICAP models, NAAPS and SILAM, carry BB smoke as a stand-alone aerosol species, although some modeling centers (e.g. NASA GMAO) have plans to separate biomass-burning BC from other anthropogenic sources to facilitate smoke-specific research and applications. Nonetheless, for the models without specific smoke species, BC and OC/POM are combined to approximate BB smoke in the ICAP-MME. Although not ideal, this approximation serves the purpose of BB smoke analysis and forecast on regional to global scales, because of BB smoke's dominant contribution to total aerosols both locally and along its transport pathways with the occurrence of fires. This is illustrated by the World Meteorological Office (WMO) application of the ICAP BB smoke product in their Vegetation Fire and Smoke Pollution Warning and Advisory System (section 6).

Five global BB emission systems are used across the current ICAP models. They are developed and maintained by the same operational or research centers for atmospheric constituent simulations:

- The Global Fire Assimilation System (GFAS; Kaiser et al., 2012) developed at ECMWF and used by CAMS, MASINGAR, MOCAGE, MONARCH and UKMO
- The Fire Locating and Modeling of Burning Emissions (FLAMBE; J. S. Reid et al., 2009) system developed at NRL, used by NAAPS
- The Quick Fire Emissions Dataset (QFED; Koster et al., 2015) from NASA, used by GEOS
- The Integrated monitoring and modeling System for wildland FIRES (IS4FIRES; Sofiev et al., 2009) from FMI, used by SILAM;
- The Blended Global Biomass Burning Emissions Product (GBBEPx) from NOAA, used by GEFS-Aerosols

These fire emission systems all use fire pixel, or gridded spatial resolutions and hourly or daily temporal resolutions that meet operational production requirements (normally within 3-hour latency). All are based on satellite fire radiative power (FRP) information because of its rapid availability for operational use. All use MODIS FRP because of its near-daily global coverage and its stability and reliability over time (French, 2023).

MODIS instruments are on board two polar-orbiting satellites, Terra and Aqua, which have local equator-crossing times of 1030 AM/PM and 1330 AM/PM local time. Despite the use of similar fundamental data sources, overall source functions are underdetermined, and processing algorithms can yield quite large differences in smoke emissions (e.g., Hyer et al., 2013; X. Pan et al., 2020). To mitigate the lack of observation of the full diurnal cycle, prescribed diurnal cycles are often applied on MODIS fire information to yield hourly BB emission. Sometimes thick cloud cover or plume prevents detections of fire hotspots from space. Additional artifacts occur from day-to-day shifts in the orbital pattern of the polar-orbiting satellites and reduce data coverage in the tropics. The potential of geostationary fire information to improve BB emission systems is widely recognized, and several groups are testing methods of integrating geostationary observations into operational global aerosol models (FLAMBE used geostationary satellite data for North and South America from 2007 to 2017). Because these models make predictions several days into the future, it is necessary to estimate the future behavior of fires. Although there is significant research on dynamic prediction of fires (Mallia, 2022), the global models of ICAP continue to use an assumption of persistence, leading to misrepresentation of emissions for days with dramatic fire evolution, such as illustrated in section 2.7.

2.4 Smoke injection height

Another challenge of modeling BB emission is emitting smoke at the correct altitudes, i.e., plume injection height, which influences how fire emissions are ultimately transported and the life cycle of smoke. Some ICAP models simply assume emissions within the planetary boundary layer (PBL) based on observational statistics, while others use plume rise models that consider the environmental status. Despite available studies on development of plume rise models (e.g., review by Paugam et al., 2016), there are unknowns in fire science (e.g. whether the fire activity and the plume dynamics are linked) and uncertainties in characterizing the overall environment. Also, none of the current ICAP models have explicit treatment of fire-induced convection or pyroconvection, which can result in smoke lofting high in the troposphere or even well into the stratosphere in extreme cases (Fromm et al., 2010; Peterson et al., 2018). Smoke injection height is strongly influenced by fire diurnal cycles (Roberts et al., 2009). Lower nocturnal injection heights are often observed because of weakened fire intensity, stable atmosphere, and lower PBL at nighttime (Sofiev et al., 2013). However intense and fast-evolving fires introduce large variabilities in diurnal cycle of plume rise, which is very challenging to represent in models.

2.5 Aerosol data assimilation

To increase the accuracy of aerosol forecasts, several centers have used data assimilation (DA) of satellite and/or ground-based observations of aerosol optical depth (AOD), which is the most widely available and evaluated aerosol parameter. Examples include 2-dimensional variational assimilation (2D var; Zhang et al., (2008)), 3D var (Randles et al., 2017), 4D var (Benedetti et al., 2009), and Ensemble Kalman filter (e.g. Khade et al., 2013; Pagowski & Grell, 2012; Rubin et al., 2017; Schutgens et al., 2010; Schwartz et al., 2014). These models often show differences in assimilation methods and assimilated AOD observations, including treatments of observations before assimilation (e.g. quality control, bias correction, aggregation, sampling). These differences occur despite consistent use of data from the MODIS (Remer et al., 2005) across all models. Work is in process to include Visible Infrared Imaging Radiometer Suite (VIIRS; Sayer et al., 2018) in some models' daily global spatial coverage. Since satellite-retrieved AOD is a column-integrated observation, aerosol speciation and vertical distribution are not constrained by assimilation of AOD. The conversion from AOD to 3-D speciated aerosol concentration/mixing ratio, and vice versa, are represented differently in the different ICAP models, adding another layer of diversity across models that include data assimilation.

Assimilation of observations of plume extent and AOD can partly correct for emission deficiencies in operational models, but extreme wildfires pose unique challenges. Often satellite retrieval algorithms fail because thick plume is misclassified as cloud. Even with retrievals, the large difference between the model state before DA and the observation creates mathematical challenges for the data assimilation system. For some fires occurring in complex terrains, the relatively coarse spatial and vertical resolution of the global models may not be able to resolve fire evolution, and this can result in transport error. For extreme fire events, even the data assimilation models have large diversity in AOD distribution and magnitude (Xian et al., 2019). AOD assimilation also does not provide vertical constraints for aerosol plume. With the uncertainties in emission height in models, assimilation of lidar-observed vertical extinction profile (e.g. from CALIOP) seemed promising, and many centers put efforts into assimilating CALIOP backscatter or extinction profiles (e.g. Cheng et al., 2019; Sekiyama et al., 2010; J. Zhang et al., 2011). However, no center is currently assimilating it in their operational mode because of limited data coverage, data latency for operational use, and requirement of high data quality for DA purposes.

2.6 ICAP Multi-Model Ensemble (MME) and its application

The motivation for developing the ICAP-MME is based on NWP studies that have shown the usefulness of ensemble-based predictions in understanding systematic errors that arise from the imperfect nature of models and the sensitivity of models to initial conditions. ICAP-MME is a consensus-style ensemble, in which all models are weighted equally. Current ICAP-MME products include analysis and 120-hr forecast of daily global speciated AOD consensus mean and spread. The smoke product is applied in the WMO Vegetation Fire and Smoke Pollution Warning and Advisory System. ICAP-MME data have demonstrated their value as a reference dataset for research and are used by many centers for their internal model evaluations. Evaluations of ICAP-MME performance in terms of fine, coarse, and total AODs show that ICAP-MME forecasts are statistically better than any individual component model overall (Sessions et al., 2015; Xian et al., 2019). The performance of ICAP-MME is relatively stable and reliable over time, even as the component models undergo significant changes. For example, AOD RMSE of the ICAP-MME is not always the lowest for a site or year or scenario, but it is relatively low and stable, unlike any of its members. Consensus MME wins in the long run because of its averaging of independent models. For probabilistic forecasting, the leading predictors for AOD forecast error are the consensus mean and spread (Xian et al., 2019). Preliminary verification of ICAP-MME using surface PM2.5 and PM10 measurements shows that ICAP-MME is the top performer among all models as well, despite more challenges in surface PM and larger divergence among the models compared to AOD simulations. Extreme smoke events remain a challenge to all models for the reasons discussed.

2.7 2020 Western United States fires as an example of challenges

The 2020 fire season in the Western United States was an excellent example of extreme events that pose a variety of challenges to operational forecast systems. The first regional event occurred in association with a mostly dry lightning subtropical disturbance on the early morning of August 16, 2020. Due in part to the high number of initiated fires, suppression crews were overwhelmed and the fires grew rapidly. With meteorology conducive for burning, the smoke spanned a total of 2000 km a day later. In this scenario, the operational models are constantly “playing catch up” with emissions. This situation demonstrates the pressing need to incorporate high-fidelity prognostic emission modelling into large-scale systems. Fire prevalence and strength further intensified into September 12, 2020, leading to thick smoke cover over the West Coast and eastern Pacific Ocean (Figure 1a), with AOD at AERONET sites in California at unprecedentedly high levels (>10). The extreme AODs resulted in retrieval failures of the densest smoke

(Figure 1b). It is not surprising that smoke simulations varied highly between centers, even after AOD assimilation (Figure 1c). Owing to evolving fire characteristics and PyroCB development, plume injection heights were highly variable from near surface to 12 km, with mid- to upper-level smoke misclassified as cirrus (e.g., CALIOP, Figure 1d), with model misrepresentation leading to advection errors. The UV-based aerosol index, a mainstay of significant UTLS biomass burning event monitoring, is nevertheless semi-quantitative in regard to assimilation, because of interdependencies on underlying clouds, single scattering albedo, and height (e.g., OMI Aerosol index, Figure 1e, Zhang et al., 2021). Despite all these challenges, the ICAP-MME was useful in forecasting smoke distribution (Figure 1f, g) and issuing warnings (Figure 1h) with forecast uncertainty estimates (Figure 1i) in such an extreme event.

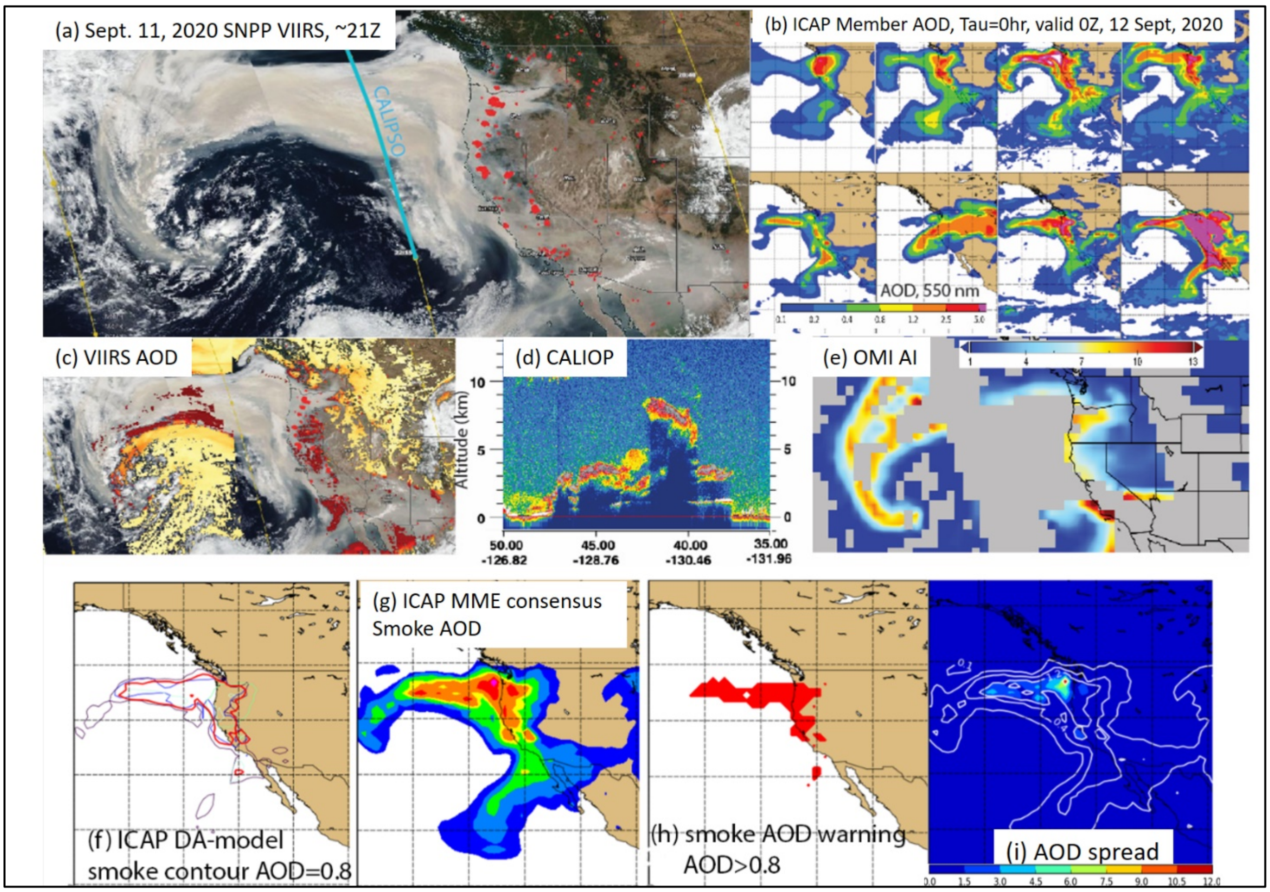


Figure 1. Mosaic of images and data products associated with 11 SEP 2020 smoke event from the Western United States. (a) SNPP VIIRS RGB (NASA Worldview); (b) VIIRS AOD showing observation extent (NASA Worldview); (c) 12 SEP 2020 0Z ICAP member model analyses of smoke AOD; (d) CALIOP expedited browse backscatter cross-section (mapped to blue track on (a)); (e) OMI Aerosol Index highest quality assurance; (f) ICAP DA-model smoke AOD contours at 0.8; (g) ICAP DA model consensus; (h) high smoke AOD (>0.8) warning; and (i) ICAP smoke AOD spread.

2.8 Future plans

Individual ICAP contributing centers have their own plans for future aerosol model developments, with each focus depending on customer needs and current model status. These plans may include separating BB smoke components to permit improved data assimilation and analysis, update of BB emission systems, improved treatments of plume rise, addition/update of aerosol data assimilation, increased model resolution, and improved parameterization of physical, chemical processes, and/or optical properties. The next steps for ICAP-MME are to develop quasi-operational surface concentration and PM ensemble forecast and increase horizontal resolution. Future advances in fire science, observation, and representation in global atmospheric constituent models are expected to improve the accuracy of smoke and air quality forecasts from the component global aerosol models as well as the ICAP-MME.

Table 1. Global Systems included in the International Cooperative for Aerosol Prediction (ICAP).

Forecast System	Operational /Research center	Status *	Smoke Products	Meteorology Model	Grid Spacing (lat x lon)	Forecast frequency and length	BB Emission System	Fire info	Plume Rise	Aerosol data assimilation	Notes and websites
CAMS	ECMWF	O	Smoke included in OC, BC tracers. Concentration all levels, PM1/2.5/10 near surface	Inline IFS	0.4x0.4	12hrly; 0Z/12Z: 120 h	GFAS 1.4	MODIS FRP	GFAS Plume Rise model	Yes. Assimilate total AOD from MODIS & PMAp	Coupled to full tropospheric chemistry based on CB05 https://atmosphere.copernicus.eu/ Rémy et al., 2019
GEOS	NASA	QO	Smoke included in OC, BC, SU, NI tracers. AOD, PM2.5, PM10	Inline GEOS	C720, output at 0.25x0.33	6hrly; 0Z: 240 h 6Z: 18 h 12Z: 120h 18Z: 18 h	QFED	MODIS FRP	PBL	Yes. Assimilate total AOD from Neural Net MODIS	https://fluid.nccs.nasa.gov/weather/ Colarco et al., 2010
NAAPS	FNMOC/ NRL	O	Smoke AOD, Concentration all levels, visibility	Offline NAVGEM	0.33x0.33	6hrly; 120 h	FLAMBE	MODIS FRP	PBL	Yes. Assimilate DAQ total AOD from MODIS	https://www.nrlmry.navy.mil/aerosol/ Lynch et al., 2016
MASINGAR	JMA	QO/O	Smoke included in OC, BC tracers; AOD, concentration all levels	Inline MRI-AGCM	0.375x 0.375	Daily; 120 h	GFAS	MODIS FRP	GFAS	Yes. Assimilate DAQ total AOD from MODIS	Tanaka and Ogi, 2018
GEFS-Aerosols	NOAA	O	Smoke included in OC, BC tracers; AOD, Concentration all levels	Inline GEFS	C384 output at 0.25x0.25	6hrly; 120 h	GBBEPx	VIIRS and MODIS FRP	Dynamic plume rise model	No.	https://www.emc.ncep.noaa.gov/emc/pages/numerical_forecast_systems/gefs_aero-test.php#
MOCAGE	Météo-France	O	Smoke included in OC, BC tracers; AOD, Concentration all levels	Offline ARPEGE	1.0x1.0	Daily; 96 h	GFAS	MODIS FRP		No.	Guth et al., 2016
MONARCH	BSC	QO	Smoke included in OC, BC tracers; AOD, Concentration all levels	Inline NMMB	0.7x0.5	Daily; 120 h	GFAS	MODIS FRP	Plume rise model	No.	Badia et al., 2017 Klose et al., 2021
SILAM	FMI	O	Smoke AOD, near-surface PM concentration	Offline IFS	0.1x0.1	Daily; 120 h	IS4FIRES	MODIS FRP	Dynamic hourly for each fire.	No.	http://silam.fmi.fi Sofiev et al., 2015
UKMO	UK Met Office	QO	AOD, near-surface PM concentration	Inline UK Unified Model	0.1x0.1 to 0.2x0.2	TBD.	GFAS	MODIS FRP	Plume rise model	For dust only.	Experimental-run for specific campaigns.
ICAP-MME	NRL	QO	Smoke AOD	-	1.0x1.0	Daily; 00Z 120 h	Website https://www.nrlmry.navy.mil/aerosol/icap.0001.php Data https://nrlgodae1.nrlmry.navy.mil/cgi-bin/datalist.pl?dset=nrl_icap_mme&summary=Go				

*Status here represents operational (O) or quasi-operational (QO).

3. The Copernicus Atmosphere Monitoring Service (CAMS) – Global and regional systems of Europe

The Copernicus Atmosphere Monitoring Service (CAMS) is a service of the European Union's Copernicus program that uses satellite Earth observations, in situ (non-satellite) data, and modeling to provide information about the composition of the atmosphere at both the global and the European scale. CAMS is implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Commission. The CAMS forecasts are implemented and carried out with the same operational commitment as the ECMWF NWP forecasts to ensure a reliable provision of the atmospheric composition forecasts.

3.1 The Global CAMS modeling and data assimilation system

CAMS provides forecasts of atmospheric composition at the global scale using the ECMWF integrated forecasting system (IFS) and at the European scale based on an ensemble of 11 regional air quality models. Satellite retrievals of ozone, nitrogen dioxide, aerosol optical depth, and carbon monoxide, as well as volcanic SO_2, are assimilated by the global system to increase the realism of the initial conditions of the forecast. The global CAMS forecast system uses the ECWMF's numerical weather prediction system at a resolution of 40 km. The atmospheric composition processes are simulated online to allow a tight coupling between weather and atmospheric composition as well as using the same four-dimensional variational data assimilation (4D-VAR) algorithm for the assimilation of satellite retrievals of weather and atmospheric composition. The IFS in CAMS configuration uses the CB05 chemistry scheme and the AER aerosol scheme (Flemming et al., 2015; Rémy et al., 2019).

Primary organic matter and black carbon originating from both biomass burning and anthropogenic sources are represented as hydrophylic and hydrophobic fractions emitted at the same rate. The ageing of OM and BC is simulated by the conversion of the hydrophobic to the hydrophylic fraction using a lifetime of 1.2 days (Rémy et al., 2019). Data assimilation of aerosol optical depth retrievals from MODIS instruments on Terra and Aqua and the Polar Multi-Sensor Aerosol product (PMAp) product is applied to improve the realism of the initial conditions of the aerosol forecast. Because AOD observations do not provide information about the aerosol speciation and vertical profiles, all aerosol components (sea salt, desert dust, OM, BC, sulphates, nitrates and ammonia) are modified by the same fraction to match the assimilated AOD observations (Benedetti et al., 2012). This means that the AOD assimilation cannot create fire plumes, but can only increase or decrease plumes already simulated by the model.

3.2 The regional CAMS system

The regional air quality production of the CAMS is based on an ensemble of eleven state-of-the-art numerical chemical transport models developed in Europe:

- CHIMERE from INERIS (France)
- EMEP from MET Norway (Norway)
- EURAD-IM from Jülich IEK (Germany)
- LOTOS-EUROS from KNMI and TNO (Netherlands)
- MATCH from SMHI (Sweden)
- MOCAGE from METEO-FRANCE (France)
- SILAM from FMI (Finland)
- DEHM from AARHUS UNIVERSITY (Denmark)
- GEM-AQ from IEP-NRI (Poland)
- MONARCH from BSC (Spain)
- MINNI from ENEA (Italy)

The models of the regional ensemble use the same anthropogenic and fire emissions and meteorological driver data. The meteorological driver data are obtained from the global CAMS system, and the same fire emissions are used in the global system and the regional ensemble. The regional models differ substantially in their chemical and aerosol schemes, deposition schemes, and the simulation of transport, diffusion, and planetary boundary layer (PBL) processes (Marécal et al., 2015). The regional models apply data assimilation of surface air quality (AQ) observation of the European AQ network for the initialisation of their forecasts. The boundary conditions of the regional models are taken from the global CAMS system to take into account long-range transport of desert dust, fire smoke plumes, and anthropogenic sources outside Europe. The forecasts of the individual regional models as well as an ensemble-mean product are presented to users. The spread of the ensemble provides information about the variable uncertainty of the regional forecast due to the aspects that vary between the regional models.

3.3 Global Fire Assimilation System (GFAS) fire emissions

The emissions from biomass burning are derived from satellite observation by the Global Fire Assimilation System (GFAS) in a timely manner and are used both in the global and regional systems. GFAS assimilates fire radiative power (FRP) retrievals from satellite-based sensors to produce daily estimates of biomass burning emissions (Kaiser et al., 2012). These daily fire emission estimates are persisted forward in the modelling systems. FRP observations currently assimilated in GFAS are the NASA Terra MODIS and Aqua MODIS active fire products (http://modis-fire.umd.edu/). GFAS data products are FRP, dry matter consumed, and biomass burning emissions for a large range of chemical and aerosol species. GFAS simulates fire injection heights, based on fire intensity and meteorological conditions using the plume rise model of Freitas et al. (2010). The GFAS data are available globally on a regular latitude-longitude grid at a horizontal resolution of 0.1 degrees from 2003 to the present. Figure 2 shows GFAS FRP from fires in Portugal in September 2020 (top left panel) and the impacts of those fires on AOD and near-surface PM2.5 concentrations across Europe from the CAMS system.

3.4 Data access and presentation

All CAMS forecast and reanalysis data, GFAS fire emission, and anthropogenic emissions are available from the CAMS atmosphere data store (https://ads.atmosphere.copernicus.eu). User support is provided for queries about scientific and technical aspects of the CAMS data. The CAMS global and regional forecast systems do not consider smoke pollution from fires in isolation. Rather, they provide that information to users integrated in atmospheric composition and air quality products. The fire signal is especially strong in the organic matter and black carbon aerosol, as well as in the carbon monoxide data. Further, the regional forecast systems distribute a specific “PM10, wildfires only” product to support the attribution of the forecast PM10 to source processes. The CAMS global and regional model and data assimilation systems and the input data are updated at irregular intervals about every 6-18 months. The changes introduced by the updates are documented on the CAMS website. The CAMS global forecasts contribute to community efforts such as ICAP (section 2), and the World Meteorological Organization (WMO) efforts described in section 6. The CAMS forecast is presented at www.windy.com for a wide range of users.

3.5 Challenges and future plans

The challenges to derive accurate fire emission data, such as the correct retrievals of FRP, and the wide uncertainty of both vegetation distribution and the biome-specific and fire-type specific emission factors, affect the performance of the global and regional CAMS air quality forecast. Of concern for smoke forecasting is the underestimation of the GFAS organic matter and black carbon fire emissions, which is compensated by applying a global correction factor of 3.4 (Kaiser et al., 2012). Although other global systems have to apply similar corrections to the OM and BC fire emissions, more research and optimization is needed to reduce the amount of the correction, for example to better understand the role of secondary aerosol formation from fire emissions.

A specific challenge of the forecast application is the prediction of the fires over the forecast period. The CAMS global and regional systems assume persistency of the GFAS fire emissions, which are derived from satellite observations from the day before the forecast start time. Progress has been made to link the weather-fire index forecasts to fire emission, especially to fill gaps based on previous FRP retrievals (e.g. Di Giuseppe et al., 2018). GFAS's next version upgrade (1.4) comprises two improvements: an increase in the temporal resolution to hourly data and an updated approach of the injection height calculation (Sofiev et al., 2012). However, the correct prediction of the duration of observed fires and the ignition of new fires remains an active area of study.

Wildfires, especially in boreal regions, are often smaller than the current horizontal resolution for the global (40 km) or regional (10 km) grid box scales as well as the GFAS resolution of 0.1 degree. Better parameters are needed to assess the effect of sub-grid scale processes on plume transport, convection, and chemical conversion.

The effect of smoke and other aerosols on weather has been successfully demonstrated with the global CAMS system. For example, smoke plumes from the intensive wildfires in the western US in 2020 led to local temperature reduction by 1-3^0 K because of the reduced radiation at the surface and reduced the bias of the 2-m temperature forecasts. However, more research and evaluation are needed before this forecasted aerosol data could improve high-resolution NWP applications in a computationally affordable way.

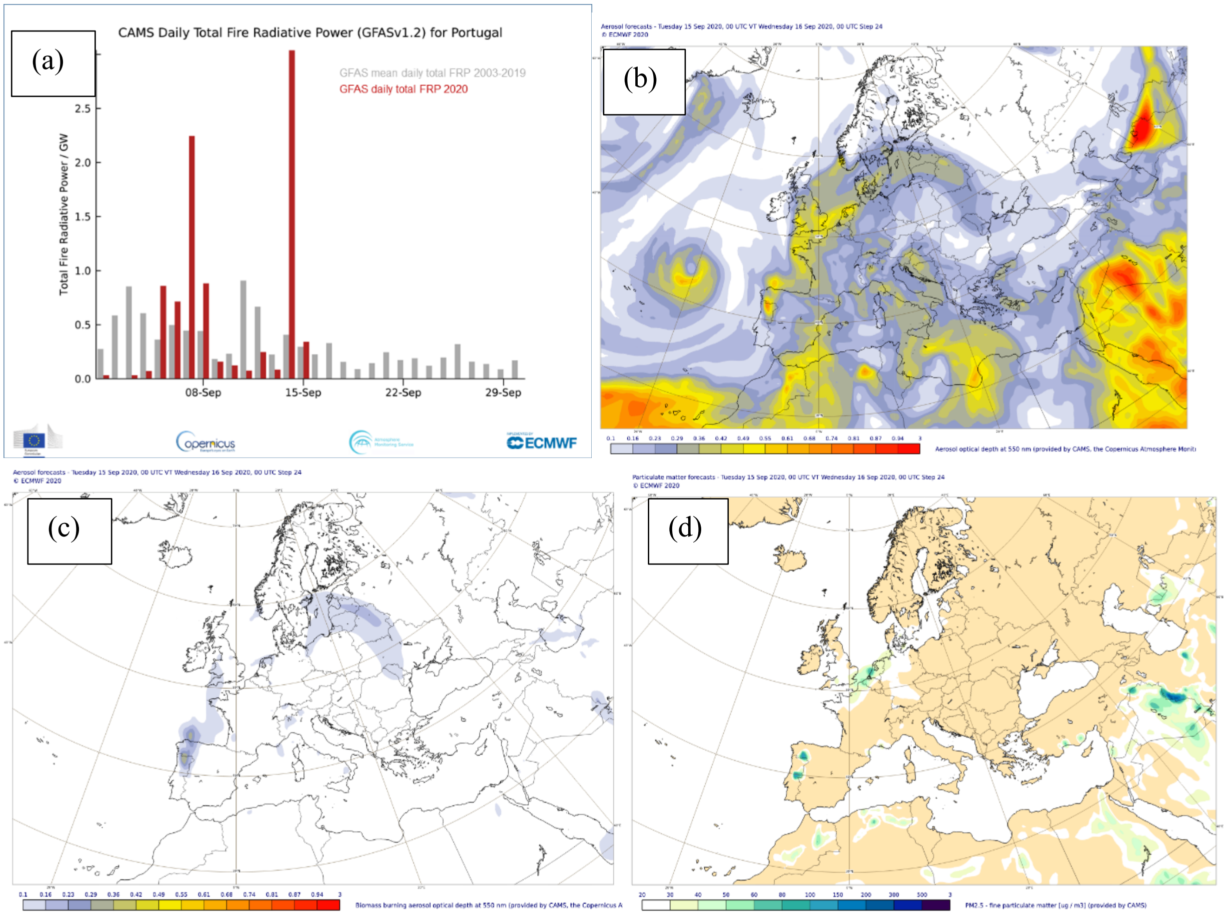


Figure 2. (a) Intensive wildfires in Portugal in September 2020 led to increased AOD and PM2.5 values. Red: GFAS total radiative fire (MODIS) values in Portugal in September 2020; grey: daily mean values for 2003-2019. The next three panels show the 24-h forecast over Europe for September 16, 2020: (b) global CAMS system for AOD, (c) biomass burning AOD, and (d) total PM2.5.

4. North American Systems

Profiled in this section are seven smoke prediction systems developed in the US and Canada by operational agencies and by universities and research groups involved in smoke and fire (Figure 3). These systems operate at scales ranging from 1 to 12 km, offering forecasts that extend 24-84 hours into the future (Table 2). The following sections are organized in approximately the system development timeline that also reflects system interconnections and collaborations. First is the BlueSky system, conceptualized in 2001 in the northwestern US when land managers and air quality agency personnel had the genesis of an idea: to build a system that relied on the many years of land manager research into forest and rangeland fuels and combustion to calculate fire emissions and input them into readily available air quality models. These fire emissions calculations and codes were then shared with the AIRPACT and NOAA NAQFC systems operating full chemical transport models. BlueSky was then ported to Canada and its development and operations were customized by the University of British Columbia (UBC). Continued years of large wildfire and smoke impacts prompted the Environment and Climate Change Canada (ECCC) to implement their operational FireWork system, building in part on the experience of NOAA NAQFC and Canadian fuel consumption research. Advancements in chemical transport modeling and computing power led to the recent NOAA HRRR-Smoke system, which relies on satellite fire emission estimation techniques and a coupled WRF-Chem system. Finally, the HiRes system in the southeastern US is tackling the challenge of prescribed burning smoke impacts using the CMAQ air quality modeling system. This section gives an overview of each of these systems, and Table 2 summarizes many of their parameters.

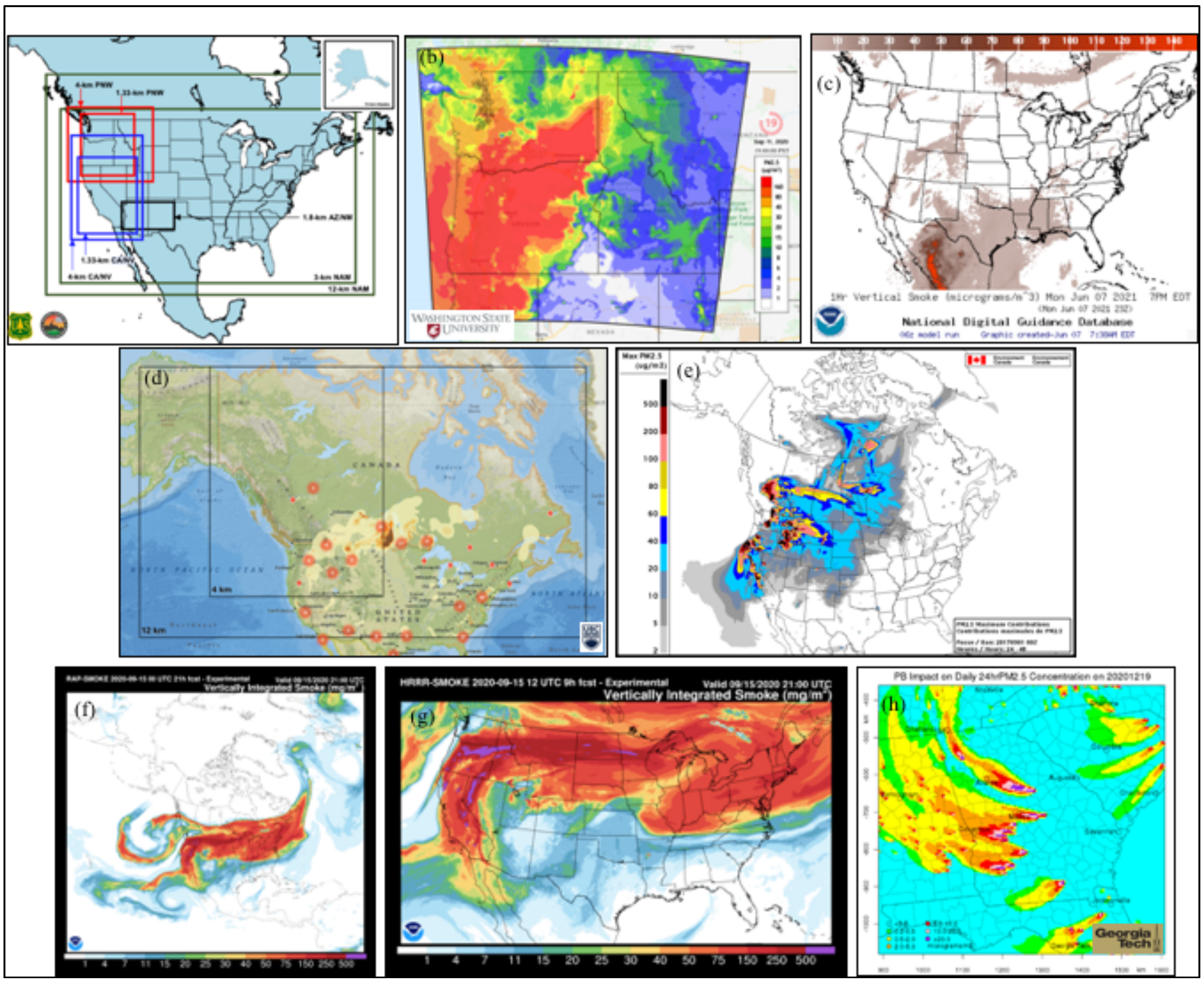


Figure 3. Domains of the north American smoke and air quality prediction systems summarized in this section. A) The US BlueSky smoke modeling framework and smoke prediction system, b) the Air Indicator Report for Public Access and Community Tracking (AIRPACT) system, c) the US National Air Quality Forecast Capability (NAQFC) system, d) The BlueSky Canada smoke forecasting system and Canadian wildland fire information system, e) FireWork Canada, f) the US NOAA operational Rapid Refresh-Smoke (RAP-Smoke) system, g) the High-Resolution Rapid Refresh-Smoke (HRRR-Smoke) System, h) the Southeastern US RiRes system.

Table 2. North American Smoke Prediction Systems

Forecast System	Operational/ Research Center	Smoke Products	Domain(s)	Meteorology Model	Grid Spacing	Forecast frequency and length	Air Quality/ Dispersion Model	Fire Activity Information	Fire Emissions	Other Sources	Plume Rise	Website
BlueSky US	USDA-FS	Ground-level PM2.5, Visibility	Various: North America, US, Regional	WRF (offline) Source: NWS, UW, DRI, UofA	Various: 1-km to 12-km	Various: 00Z, 06Z, 12Z, 18Z Various: 36 hr to 84 hr	HYSPLIT, CMAQ (no chemistry, smoke PM2.5 as tracer)	Fire Information System (FIS): VIIRS (S-NPP and NOAA-20) and MODIS (Terra and Aqua), GOES-16 ABI. Persistence	BlueSky Pipeline	None	FEPS-Briggs	https://tools.airfire.org
AIRPACT5	WSU, NW-AIRQUEST	Ground-level: PM2.5, O3, NOx, CO, visibility, SO2, NH3, other VOCs	Northwestern US, including states of Idaho, Oregon, and Washington	UW WRF runs on 4-km grid (nested within 12-km and 36-km runs) initialized with GFS at 00Z. (offline)	4-km	Daily; 48 hr	CMAQ v 5.0.2, CB05 chem, aero5 aerosol physics	USDA-FS Fire Information System (FIS). Persistence	BlueSky Pipeline	NEI 2017, MOVES, Biogenic emissions from MEGAN 2.10, WACCM boundary conditions	DEASCO3 from WRAP with IDEQ parameter-ization for heat.	http://lar.wsu.edu/airpact/
NAQFC	NOAA	$PM_{2.5}$, OC, BC, O_3, NOx, CO, NH_3, AOD	Continental US	Various. Always driven by NWS operational weather models (offline)	12-km	Daily; 48 hr	CMAQ v 5.0.2/v5.3	HMS; VIIRS, MODIS and GOES-16. Persistence	BlueSky, GBBEPx	NEI2016v2; BEIS for biogenic, and FENGSHA for dust	Briggs (1969) and Sofiev (2012)	https://airquality.weather.gov
BlueSky Canada	UBC	Ground-level PM2.5	North America, west coast of North America	WRF	12-km; 4-km	12-km: 00Z, 06Z, 12Z, 18Z 4-km: 00Z 51 hr	HYSPLIT	AVHRR, MODIS, VIIRS (from CWFIS/SF2). Persistence	CWFIS/ BlueSky	None	FEPS-Briggs	https://firesmoke.ca
FireWork / RAQDPS-FW v021	ECCC	Surface and vertically integrated $PM_{2.5}$ (public); O_3, NO_2, PM_{10}, NO, CO, surface visibility etc. (by request). Offline analysis for health effects.	North America, Canada	Global Environmental Multiscale model (GEM v5.0) (inline)	10-km	00Z, 12Z 72 hr	GEM-MACH v3.0	VIIRS (S-NPP and NOAA-20) and MODIS (Terra and Aqua) – from the Canadian Wildland Fire Information System (CWFIS). Persistence (past 24 hr hotspots)	CWFIS/ CFFEPS	Emission set 3.1.2: APEI 2013 v1, 2017 projection of NEI 2011 v3, 2008 Mexico Biogenic BEIS v3.09	Canadian Forest Fire Emission Prediction System CFFEPS v2.06	Public: https://weather.gc.ca/firework Open data: https://eccc-msc.github.io/open-data/msc-data/nwp_raqdps-fw/readme_raqdps-fw_en

HRRR-Smoke	NOAA	Weather, PM2.5 (ground-level and total column), surface visibility	Continental US and Alaska	High-Resolution Rapid Refresh (Inline)	3-km	Every hour a new forecast is produced. Forecast lengths are 48 hours every 6 hours, otherwise 18 hours.	WRF-Chem, Smoke PM2.5 tracer. No chemistry. Includes smoke feedback effects on radiation and surface visibility.	VIIRS (S-NPP and NOAA-20) and MODIS (Terra and Aqua). Persistence	FRP	None	Freitas (2007)	https://rapidrefresh.noaa.gov/hrrr/HRRRsmoke/ https://rapidrefresh.noaa.gov/hrrr/HRRR-AKsmoke/,
HiRes2	Georgia Tech	O_3, $PM_{2.5}$, health effects	Southeastern US	WRF 3.8 with GFS 0.25-degree forecasts (offline)	4-km	Daily; 24 hr	CMAQv5.0.2 with DDM	Statistical analysis: GA burn permit and GBBEP fire information in the US Southeast for 2010-2016	Mapped fuels (FCCS), measured fuel moisture, emission factors	NEI-2011	Empirical model of Liu (2014)	https://forecast.ce.gatech.edu & https://sipc.ce.gatech.edu/SIPFIS/map/

4.1 US BlueSky Smoke Modeling Framework and Smoke Prediction System

The BlueSky Smoke Modeling Framework (Larkin et al., 2009), first released in 2002, was developed by the US Forest Service Research, in conjunction with partners, to compute fire emissions and smoke impacts. BlueSky's original motivation was the need to better predict potential prescribed fire smoke impacts in order to mitigate or avoid them prior to ignition. However, BlueSky has evolved and is now used in both research and in operational contexts for both prescribed burns and wildfires, and it is incorporated into multiple operational daily forecasts and tools.

One unique aspect of BlueSky is that it is open-source and modularly combines databases and models across seven modeling steps: fire information, available fuels, consumption, emission factors, time release, plumes, and atmospheric dispersion and chemistry, providing specific application programming interfaces (APIs) for incorporation of new modules. This allows for the addition of newer models and databases as they become available. Because BlueSky is a framework that incorporates multiple model options at each step, caveats and assumptions are pathway-dependent. The largest assumptions for fire concern the ability to correctly identify burning areas, the amount of fuel available; for smoke impacts, key assumptions concern the timing of the emission throughout the day and their plume injection heights (e.g. Drury et al., 2014; Larkin et al., 2014; Larkin et al., 2012; Prichard et al., 2019; Raffuse et al., 2012). For retrospective analyses when assumptions can be better specified, the system performs with Pearson correlation of about 0.65 and a positive bias of 7-9 $\mu g/m^3$. Data assimilation improves these results (O'Neill et al., 2021; Zou et al., 2019) but with a negative bias tendency (O'Neill et al., 2021). Analyses such as these helped justify the need for new coherent multi-faceted observational campaigns to help advance the state of science in these areas, such as the Fire and Smoke Model Evaluation Experiment (Brown et al., 2014; Prichard et al., 2019).

The identification of burning areas has been a large source of development, with various approaches that combine satellite data and ground reports in both real-time and retrospective ways, including SmartFire v1 and v2 (Raffuse et al., 2009), and the newer Fire Information System (FIS; Marsha & Larkin, 2022). FIS aggregates fire detection information from the MODIS, VIIRS, and GOES-16 ABI instruments to create air quality model-ready fire activity datasets; these account for redundant fire identifications from the multiple sources, false positive detections from anthropogenic sources, and dropouts when smoke obscures the satellite ability to see the fire. FIS includes a statistical analysis of multiple years of satellite fire detections from the individual satellite instrument data streams to estimate a fire size per detection. Fire radiative power (FRP) is carried through the data stream and also aggregated to an independent grid, both of which can be used in downstream fire emission and plume rise calculations.

BlueSky has multiple operational applications. It is used as an emission processor for the biomass burning component of the U.S. National Emissions Inventory (Larkin et al., 2020). It is also used in web tools such as BlueSky Playground that allow fire managers to customize and interactively calculate fire emissions and smoke impacts for specific fires of concern (both prescribed burns and wildfires). This functionality is also automated in some prescribed fire reporting systems. BlueSky is also incorporated into multiple operational smoke forecasting systems with different types of fire information and purposes.

The U.S. Forest Service uses BlueSky to perform a number of daily runs that focus on the needs of incident support. Over 30 model runs are performed daily using a variety of meteorological model forecasting domains across the country. Some of these domains are large-scale (e.g. from the U.S. National Weather Service's Global Forecast System), but the emphasis is on high-resolution forecasting at typical scales of around 1.33-km grid resolution. Meteorological forecasts for these high-resolution runs come from a variety of partners, including regional modeling consortia such as the Northwest Regional Modeling Consortium and the California and Nevada Smoke and Air Committee (CANSAC). These forecasts are supplemented during heavy fire and smoke periods by movable high-resolution (1.27-km) fire weather domains managed by the U.S. National Weather Service to cover affected areas.

All of these runs, as well as those from other systems, are used by deployed smoke specialists from the U.S. Interagency Wildland Fire Air Quality Response Program (IWFAQRP; Lahm & Larkin, 2020) to develop smoke outlooks that provide consistent messaging and forecasting in affected areas. These smoke specialists use the model runs to develop these tailored forecasts, which are then used by the fire, health and air quality agencies, and the public. A unique aspect of this system is that the smoke specialists can affect the BlueSky Daily Runs by obtaining ground information (e.g. fuel types, loadings, and fuel moistures) observed by fire personnel, as well as fire growth projections done in support of the incident; this information can then be used within the context of the daily runs, creating customized smoke model predictions. These customized runs, the standard daily runs, and other BlueSky-related tools such as the U.S. BlueSky Playground, are available through the IWFAQRP tools page (https://wildlandfiresmoke.net/tools).

4.2 Air Indicator Report for Public Access and Community Tracking (AIRPACT)

The Air Indicator Report for Public Access and Community Tracking (AIRPACT) project (http://lar.wsu.edu/airpact), begun in 2000, built upon air pollution modeling experience at the Laboratory for Atmospheric Research (LAR) (Barna et al., 2000; O'Neill & Lamb, 2005; O'Neill et al., 2006; Richter et al., 2004; Snow et al., 2003) to create a forecasting system for the US Pacific Northwest (Vaughan et al., 2004). In 2003, the Northwest International Air Quality Environmental Science and Technology (NW-AIRQUEST) Consortium was created to obtain scientific input for air quality management decisions in the Pacific Northwest, providing funding and agency-oriented guidance for the AIRPACT project (http://lar.wsu.edu/nw-airquest/index.html). Consortium members include federal, state, local, and tribal environmental engineers and air-quality scientists.

AIRPACT evolved with improvements to emissions inventories, modeling systems, and computing power, which allowed greater complexity, resolution and domain extent as well as longer forecasts (J. Chen et al., 2008; Mahmud, 2005; Vaughan et al., 2004). AIRPACT version 5 (AIRPACT5) has a 4-km grid that covers Washington, Oregon, Idaho, and surrounding areas. It uses the Community Multi-scale Air Quality (CMAQ; Byun & Schere, 2006) modeling system with the CB-05 chemical mechanism, a full emission inventory of natural and anthropogenic sources, and meteorology from the Weather Research and Forecast model (WRF v4.1.3; W. C. Skamarock, 2004) from the University of Washington (Mass et al., 2003; Ovens & Mass, 2020). Anthropogenic emissions are from the EPA 2017 National Emission Inventory (NEI; Larkin et al., 2020). Biogenic emissions are from MEGAN 2.10 (Guenther et al., 2006), as parallelized by LAR for timely execution to meet forecasting time constraints. Dynamic boundary conditions are obtained from the Whole Atmosphere Community Climate Model (WACCM) daily forecast results (Gettelman et al., 2019). Initial conditions for each AIRPACT run are obtained from the previous run. Forecast length is 48 hours; model runs begin at ~2200 local time and finish the first of the two forecast days by 0700 local time the next morning.

AIRPACT5 gets wildfire emissions from the US Forest Service Research fire information system (FIS) linked with the BlueSky system with three options: “dropouts” to include fires detected recently but not in the latest satellite imagery, “persisted” to project current fires forward in time, and “mean area” to specify fire area per fire location. Heat released is estimated from fire area and Fuel Characteristic Classification (FCCS; McKenzie et al., 2007) fuel type, then applied in a plume rise scheme based on the Deterministic and Empirical Assessment of Smoke's Contribution to Ozone Project (DEASCO3) algorithm (Moore et al., 2013) as parameterized by the Idaho Department of Environmental Quality (DEQ, 2017).

Wildfire smoke has recently become intense and common enough that WRF forecasts for AIRPACT5 showed surface temperature biases due to unaccounted-for aerosol feedbacks. To better capture the temperature effects of smoke, since August 2020 AIRPACT5 WRF runs use aerosol optical depth and the aerosol Angstrom exponent fields from NASA's GEOS system in the radiation scheme (Ovens & Mass, 2020).

For each monitoring site, the AIRPACT5 website includes monthly performance evaluation statistics and flexible charting for ozone and PM2.5. Munson et al. (2021) documented the evolution of components and model versions for AIRPACT3, 4, and 5, and forecast skill for 2009-2018. For AIRPACT 3, 4, and 5, respectively, PM2.5 normalized mean bias was -25%, -31%, and -35%, and PM2.5 normalized mean error was 31%, 35%, and 44%. The statistics trend downward (worsen) over time, likely reflecting progressively greater effects of wildfires over that decade.

All components of a deterministic smoke forecasting system contribute to forecast error, so LAR recently augmented AIRPACT's forecasting with two other approaches, bias correction and machine learning. AIRPACT5 24-h average PM2.5 biases are computed using a Kalman filter for all PM2.5 monitoring sites, then interpolated using Kriging to create a continuous bias correction field for correction of the AIRPACT5 daily 24-h PM2.5 forecast (June et al., 2021). The Kalman filter bias correction shows improvements for both winter and wildfire month biases, (about -50% ±6% annualized), and the corrected results also had much smaller mean absolute errors (typically <20%). Machine learning applies a random forest classifier and multiple linear regression models, trained on recent history, to forecast O3 and PM2.5 at monitoring sites (Fan et al., 2020).

4.3 US National Air Quality Forecast Capability (NAQFC)

The US National Air Quality Forecast Capability (NAQFC) forecasts, operated by the National Weather Service (NWS), provide real-time prediction of ozone, fine particles (PM2.5), smoke, and dust over the Continental United States (CONUS), Alaska (AK), and Hawaii (HI) (J. Huang et al., 2017; P. Lee et al., 2017; L. Pan et al., 2014; X. Pan et al., 2020; Tong et al., 2015). NAQFC is one of the key tools widely used by state and local agencies to protect the public from exposure to elevated levels of air pollutants. During wildfire events, accurate prediction of fire emissions, chemical transformation, and transport are critical for air quality forecasters to issue early warning to protect human health (Tong & Tang, 2018). The NAQFC system uses various versions of the Community Multiscale Air Quality (CMAQ) model (Byun & Schere, 2006) to provide next-two-day prediction of surface O_3 and PM2.5 concentrations over all 50 US states, using three regional model domains (CONUS, AK, HI). Inputs to the CMAQ model include meteorological data from NOAA's operational weather forecasting model, anthropogenic emissions from national emission inventories from the US, Canada and Mexico, natural source emissions derived using satellite retrievals or emission model estimation, and lateral boundary conditions from global chemical transport models (P. Lee et al., 2017; X. Pan et al., 2020; Tang et al., 2021; Tong et al., 2015).

Several products of biomass burning have been used or are being tested under NAQFC to predict wildfire air quality (Y. Li et al., 2020; X. Pan et al., 2020). Previously, the current operational forecasting was based on the BlueSky emission algorithm (Larkin et al., 2009) driven by fire detection from the NOAA Hazard Mapping System (HMS) (P. Lee et al., 2017; X. Pan et al., 2020). The HMS fire detection products used to be produced manually by a team of human operators. The operator-based fire screening has since been replaced by an automatic fire detection algorithm. This switch has sharply increased the false alarm rate (false fire detection), causing the NAQFC to temporarily remove biomass burning emissions to avoid widespread degradation of model performance for surface O_3 and PM2.5. The team has assessed alternative fire emission products for large wildfire events during the 2018 Camp Fires in California (Y. Li et al., 2020). In July 2021, the wildfire emissions in NAQFC was updated based on the Global Biomass Burning Emissions Product (GBBEPx, X. Zhang et al., 2012; X. Zhang et al., 2014), and plume rise algorithm based on Sofiev et al. (2012).

4.4 The BlueSky Canada Smoke Forecasting System and Canadian Wildland Fire Information System

The Weather Forecast Research Team (WFRT) at UBC in Vancouver, Canada, adapted the BlueSky smoke forecasting system (Larkin et al., 2009) for Canada (BlueSky Canada, BSC) and has operated it since 2010. BSC uses inputs of fire information and meteorology to estimate fire emissions, initial smoke plume-rise, and subsequent smoke dispersion. Meteorology is from the Weather Research and Forecast model (WRF v4.2.1; Powers et al., 2017; C. Skamarock et al., 2019), also operated by the WFRT, with three nested domains: 36-km grid spacing covering North America, 12-km over most of Canada and the US, and 4-km over the complex terrain of western Canada. The hourly evolution of emissions for each fire, initial plume rise, and meteorology are input to the HYSPLIT dispersion model (Draxler, 1999; Draxler & Hess, 1997, 1998; Stein et al., 2015). HYSPLIT is run with two domains: at a 0.1° (~11 km) grid spacing covering North America using the 12-km meteorology, and at a 0.05° (~5 km) grid spacing covering western Canada using the 4-km meteorology. The smoke forecasts have a 51-hour forecast horizon. BSC runs four times daily for the larger domain (initialized with meteorology spaced 6 hours apart) and once a day for the smaller domain (Table 2).

The Canadian Wildland Fire Information System (CWFIS; NRCan, 2020) provides fire location and fuel consumption to BSC. It relies on satellite data from the Advanced Very High-Resolution Radiometer (AVHRR), the Moderate Resolution Imaging Spectroradiometer (MODIS), and the Visible Infrared Imaging Radiometer Suite (VIIRS) instruments. Hotspots are sometimes obscured from the view of satellites by clouds or even smoke from fires, or they may be too small to be detected. Thus, the CWFIS also includes ground reports of fire locations. The CWFIS produces fire weather and fire behavior products and comprises a number of subsystems, two of which BSC depends upon:

- Fire Monitoring, Mapping, and Modeling (Fire M3) system: Actively burning fires are detected by infrared satellite imagery and used to estimate daily and annual area burned, as well as to model fire behavior and forecast smoke;
- Fire Behavior Prediction (FBP) system: Fire behavior parameters such as rate of spread, fuel consumption, and fire intensity are predicted from inputs of fire weather indices, along with fuel types, topography, and other factors.

During the fire season, Fire M3 is run four times daily to generate updated fire location data. Consumption information is obtained from the FBP system. For ease of modeling and to prevent ingesting duplicate fires, the raw fire information runs through the Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation (SMARTFIRE), version 2 (SF2). SF2 associates fire locations into clusters to minimize duplicates from multiple satellite data sources, links them with known fire events, converts the cluster to point data, and assigns an area burned to the points (Raffuse et al., 2009). The output from SF2 is a CSV file that includes SF2 fire perimeters, locations, and fire fuel consumption, all of which is input to BSC. Each time BSC is run, it retrieves the most recent and up-to-date SF2 data.

The fire growth module within BSC uses a simple persistence model, in which the area growth on the first day also occurs on the next two days. Each day of the forecast, BSC assumes that all fires grow linearly between 0900 and 2100 local time. Knowing the area growth for that period, and the total fuel consumption for that area, fire emissions are estimated using the Fire Emission Production Simulator (FEPS; Anderson et al., 2004), which gives hourly measures of PM2.5 emissions and heat release. FEPS also computes the initial smoke plume rise, based on modeled heat release using the Brigg's plume-rise model (Briggs, 1972, 1982).

The BSC output of smoke PM2.5 concentrations at 10 m above ground level is available at a public website (https://firesmoke.ca/) and in several formats. The most popular is the animated Leaflet display, widely used by provincial government health and environmental agencies to issue health warnings and advisories, emergency responders, Canadian residents and tourists, and the media. The outputs are also available as three kinds of files: KMZ files, which can be loaded into Google Earth and compared with satellite images, geoserver files for input by provincial agencies to use in their fire-data management systems, and netCDF files for scientific analysis. A near-real-time quantitative verification system helps identify major issues, such as missing fires. Future plans include a new fire weather index (FWI) and FBP system, outputting column-integrated smoke, including the process of wet deposition of smoke during dispersion, and implementing a new plume rise model (Moisseeva & Stull, 2021).

4.5 FireWork Canada

Boreal forests, which comprise approximately 75% of Canada's landmass, frequently experience biomass burning as part of the natural ecosystem lifecycle. However, with the signature of a changing climate, these fires are becoming larger, more intense, and are occurring closer to the wildland urban interface (Tymstra et al., 2020; Wotton et al., 2017). ECCC meteorologists responsible for issuing the air quality forecast under the Air Quality Health Index program (AQHI; Stieb et al., 2008) needed better numerical guidance to quantify and predict the contribution of biomass burning to PM2.5 concentrations. There was also a growing expectation for the MSC to deliver smoke dispersion products similar to those successfully produced by the BlueSky Canada initiative (section 4.4). Since 2016, the Meteorological Service of Canada (MSC), part of ECCC, operates a regional air quality deterministic prediction system with fire emissions, known as FireWork (J. Chen et al., 2019; Pavlovic et al., 2016).

The development of FireWork took full advantage of the MSC's operational NWP supercomputing environment and leveraged existing air quality forecast model infrastructure. FireWork uses the Canadian GEM-MACH chemical transport model (Moran et al., 2018; Moran et al., 2019; Moran et al., 2014), coupled online with the GEM numerical weather prediction model (Côté et al., 1998; Girard et al., 2014). Its codebase and configuration are synced with those used for the GEM-driven Regional Deterministic Prediction System, so FireWork inherits regular innovations to the dynamics and physics components, as well as weather data assimilation. Here we describe version 2.0 of FireWork, implemented in operations in 2019 as the Regional Air Quality Deterministic Prediction System with Near-Real-Time Wildfire Emissions (RAQDPS-FW) version 021 (J. Chen et al., 2019).

Similar to WFRT's BSC system described previously (section 4.4), FireWork relies on Canadian Forest Service's (CFS) CWFIS for near-real-time input of fire location, fuel parameters and estimated daily burn areas. However, unlike BSC, FireWork implements the Canadian Fire Emissions Prediction System

(CFFEPS) for near-real-time calculations of fire emissions and plume injection heights for input to the GEM-MACH chemical transport model. CFFEPS was developed jointly by ECCC and the CFS, NRCan, and uses a bottom-up, process-based approach to compute hourly wildfire emissions. Biomass fuel consumption is estimated with hourly input forecast meteorology, and surface fuel parameters. Crown and surface fuel consumptions are calculated by the Canadian Forest Fire Behavior prediction system (FBP, Forestry Canada, 1992) for flaming, smoldering and residual combustion fractions. These quantities are converted to hourly emissions with emission factors by combustion processes. Additionally, smoke injection height and emission vertical distribution are parameterized based on fire-energy thermodynamics and forecast temperature profiles at individual fire hotspot locations. Emissions enter the GEM-MACH air quality model as major point sources, with treatment for chemical speciation differentiated for smoldering and flaming combustion phases. Wildfire emissions are added to other anthropogenic and biogenic emissions to provide a complete picture of air pollutant sources across the North American domain.

To capture all significant emission sources that affect Canada, FireWork is implemented on a continental domain that includes all of the contiguous US and most of Canada and Alaska. A twin system is run without fire emissions, which allows a first-order approximation of the attribution of forecast pollution to wildfire sources through the calculation of differences in forecast concentrations. FireWork inherits the multi-phase, multi-pollutant chemistry from GEM-MACH which includes gas-phase, aqueous-phase, and heterogeneous chemistry; aerosol processes; secondary organic aerosol chemistry; and deposition processes. This enables FireWork to capture the evolution and impact of wildfire pollution over both regional and continental scales.

Twice a day (00 and 12 UTC), the system produces a North America-wide, 72-hour model forecast of air pollution, with PM2.5 surface and total column concentrations, as well as surface NO_2 and O_3. The simulation results provide numerical guidance on regional air quality conditions to MSC forecasters in regional offices. The forecasters issue public air quality forecasts in the form of the Air Quality Health Index (Stieb et al., 2008) as well as smoke-related special weather bulletins. Products such as maps of extinction coefficient, and time series of visibility degradation in statue miles at airports are also becoming available (So et al., 2018).

FireWork is routinely evaluated with surface observations as part of system performance tracking, and fire emissions and plume injection heights are evaluated with available remote sensing measurements (Adams et al., 2019; Griffin et al., 2020). Additional applications also include using it in a long-term surface analysis of fire-$PM_{2.5}$ concentrations (Munoz-Alpizar et al., 2020). These hourly analyses provide a valuable option as a source of long-term exposure data to the health community. FireWork forecast products for the attribution of surface PM2.5 concentrations to fires have also been used to assess the cost of fire smoke impacts on health in Canada (Matz et al., 2020).

Active research is underway towards coupling CFFEPS with GEM-MACH for closer linkages between fire behavior and meteorology, and accounting for the direct and indirect feedbacks between air quality and meteorology (Makar et al., 2020; Ye et al., 2021). These research studies are part of the planned improvements to FireWork operational implementation which also include the introduction of dynamical interaction of plume aerosols with meteorology, hotspot aggregation methods, a data assimilation cycle for atmospheric constituents, and finer resolution domains. For the latest information on the operational FireWork system, please refer to the Meteorological Service of Canada open data documentation at https://eccc-msc.github.io/open-data/.

4.6 US NOAA Operational Rapid Refresh-Smoke (RAP-Smoke) and High-Resolution Rapid Refresh-Smoke (HRRR-Smoke) Forecast Systems

The US NOAA Global Systems Laboratory (GSL) is one of the world leaders in development of numerical weather and air quality forecast models. NOAA/GSL developed the Rapid Refresh (RAP) and High-Resolution Rapid Refresh (HRRR) weather forecast systems (Benjamin et al., 2016). The RAP domain covers the entire North and Central Americas (13.5 km domain resolution), and the HRRR grids cover the CONUS and Alaska domains (3 km domain resolution; Figure 3f,g). An important feature of these models is their rapid update cycle. Every hour a new RAP and HRRR CONUS forecast starts by assimilating the latest meteorological observations, including the radar data to provide storm-scale weather forecasts to stakeholders. For HRRR-Alaska the refresh cycle is three hours.

In 2016, NOAA/GSL began experimental smoke forecasting by implementing a smoke tracer (fine particulate matter from fires) to the HRRR model (HRRR-Smoke) over CONUS, then expanded this capability to the RAP and HRRR-Alaska models. In both RAP-Smoke and HRRR-Smoke models, the biomass burning (BB) emissions are estimated in real time by using the fire radiative power (FRP) data from four satellite platforms: two from VIIRS (S-NPP and NOAA-20) and two from MODIS (Aqua and Terra) satellite platforms (Ahmadov et al., 2017). The FRP data are also used to estimate the fire heat flux and fire size to simulate the plume rise of the fires in the models (Freitas et al., 2007). The advection, boundary layer and convective mixing, and dry and wet deposition processes for smoke are included. The RAP-Smoke model provides lateral boundary conditions of smoke to the HRRR domains in real time. Thus, HRRR-Smoke can capture smoke transported from the wildfires in Canada and Central America (RAP domain) into the CONUS (HRRR) domain. The simulated smoke tracer is cycled between the subsequent model forecasts.

Because the HRRR has a high spatial resolution (3 km), advanced dynamics, and storm-scale forecasting capabilities, it simulates the smoke transport in a convective environment and over the complex terrain reasonably well. The hourly refresh cycle of RAP/HRRR-Smoke helps to initialize newly started wildfires into the model after they are detected by the polar orbiting satellites with short delays.

The coupled framework of the RAP/HRRR-Smoke modeling systems enables simulation of the effect of smoke on solar radiation, which, for example, can cool near-surface temperature. This ability helps improve the weather forecasting skill of the RAP/HRRR models in regions affected by dense smoke. NOAA/GSL has shown significant improvement in air temperature and surface visibility forecasting during wildfire and smoke events that have recently occurred in the US, particularly in the western regions.

After extensive testing and improvements, in December 2020 NOAA/GSL transitioned the smoke forecasting capabilities to NOAA's operational RAP/HRRR models. The hourly operational forecast cycles now produce multiple meteorological, smoke and visibility forecast products. Respectively, the RAP-Smoke and HRRR-Smoke forecasts go out to 21 and 18 hours, with forecast lead times of 51 and 48 hours four times a day. The operational RAP/HRRR-Smoke forecast models provide hourly 3-D smoke forecast and diagnostic products (e.g. vertically integrated smoke) to users within the standard model output files in GRIB2 format. The near-surface smoke and forecast products are displayed on NOAA/GSL's public website (https://rapidrefresh.noaa.gov/hrrr/HRRRsmoke/).

Weather and air quality forecasters, air resource advisors, private sector forecasters and the public all use the model forecasts, especially the fine-scale HRRR-Smoke forecasts over the CONUS domain. During the intense fire seasons in 2018 and 2020 (Figure 3f,g), the HRRR-Smoke forecasts were a critical tool for numerous US stakeholders. In addition to forecasts of smoke impacts on air quality and visibility, HRRR-Smoke forecasts are used to determine the impact of dense smoke on weather.

NOAA/GSL, in collaboration with other modeling and satellite teams, is working to transition the smoke forecasting capability to the next-generation regional NWP model based on the Finite-Volume Cubed-Sphere dynamical core. Besides the new model dynamics and physics schemes, other major improvements are planned to implement in the future FV3 based smoke forecasting model, such as ingesting the GOES-

16/17 FRP data and improving the diurnal cycle of the BB emissions. A new hourly fire weather index is also being developed for use with the next-generation NWP system, both to predict wildfire danger and to modulate future smoke emissions from existing fires.

4.7 Southeastern US

Prescribed fire is the leading source of PM2.5 emissions in the US Southeast (EPA, 2017), and its share is growing as the use of agricultural and silvicultural burning increases while other sources are subject to stringent controls. Especially during the burning season (January-April), the region's air quality is adversely affected by prescribed fire smoke. HiRes2 (Odman et al., 2018) was designed to forecast prescribed fire smoke and air quality in a portion of the southeastern US centered around Georgia. Supported initially by the US Environmental Protection Agency and later by the NASA Applied Sciences Program and the Joint Fire Science Program, its goal is to provide air quality and forest managers with the air quality information they need for day-to-day management of burning operations.

Prescribed burning decisions are typically made on short notice based on weather forecasts. Compared to wildfires, prescribed burns are of shorter duration and produce relatively low heat. This makes both their detection and estimation of their emissions by satellite very difficult (R. Huang et al., 2018). Because of these factors, persistence of fire activity information into the future is a particularly poor assumption for prescribed fires. To overcome these difficulties, HiRes2 starts with a forecast of prescribed fire activity based on (1) the weather forecast, generated by running WRF (and later used to drive CMAQ), and (2) historic burning patterns, derived from the 2010-2016 burn permit databases for Georgia and 2015–2016 GBBEP (Zhang et al., 2012, 2014) data for other states. This unique aspect of HiRes2 is enabled by a decision tree model that yields potential burned areas for likely burn locations. The prescribed fire emissions are calculated from the FCCS fuel bed maps at those locations, fuel moistures reported by the Fire Weather Network, and emission factors for southeastern US fuels published by the US Forest Service (Urbanski et al., 2009). An empirical plume rise model (Liu, 2014) is used to distribute those emissions to the vertical layers of CMAQ. Emissions from other anthropogenic sources are derived from the EPA National Emission Inventory (NEI), and biogenic emissions are obtained by running the Biogenic Emission Inventory System (BEIS; Fehsenfeld et al., 1992) with the WRF-generated weather forecast. The contributions of prescribed fire emissions are tracked using the Direct Decoupled Method (DDM; Napelenok et al., 2008) in CMAQ.

The fire activity forecast is compared daily with the NOAA Hazard Mapping System (HMS) Fire and Smoke Analyses (X. Hu et al., 2016) and evaluated qualitatively, based on the agreement of the location and density of the fires. The agreement is generally good on days with heavy fire activity. Quantitative evaluations are also performed periodically through comparisons with data in prescribed fire records. The R^2 of linear regression between the forecast and permitted daily statewide total burn areas in Georgia during the 2015 burn season was 0.34 (Y. Hu et al., 2019). Forecast contributions to PM2.5 air quality are evaluated through comparisons to PM2.5 observations at regional monitors; this is done on days of reporting exceedances of the national ambient air quality standards (daily average PM2.5 > 35 $\mu g\ m^{-3}$). The precision, recall, and F1 score for correctly predicting the prescribed fire impacts in exceedances during the 2016 burn season were 19%, 36%, and 25%, respectively (Odman et al., 2018).

Through the permitting systems already in place in several southeastern US states, prescribed burns can be restricted on expected poor air quality days and encouraged when meteorological conditions are more favorable. The use of HiRes2 forecasts in this manner may lead to increased burn capacity while reducing the impacts on air quality and human health from exposure to high levels of smoke (R. Huang et al., 2019).

HiRes2 is undergoing a major update and expansion; the new system will be called HiRes-X. The domain of the forecast will be extended and all modeling components will be updated to their latest versions. The decision tree model for the burn activity forecast will be replaced with a random forest machine learning algorithm (Zou et al., 2019), trained by updated fire information. Current health impact forecasts are based on studies of exposure to wildfire smoke (Alman et al., 2016b). To document relationships between smoke from prescribed fire and health, the association between prescribed fire smoke and rates of ED visits across the Southeast will be analyzed for 2015-2021, and exposure-response profiles specific to prescribed fire smoke will be derived for cardiopulmonary and other diseases.

5. Smoke forecasting in Australia

Wildfires (e.g. bushfires) have been a significant natural feature of the Australian landscape for millennia, as illustrated by the extent of savanna burning in northern Australia (Figure 4). Annual fire frequencies are linked to regional weather patterns and drought as well as more than 45,000 years of land management by First Nation communities (Bowman et al., 2020). More recently, the number of extreme fire events have increased (BOM, 2020b), culminating in an unprecedented bushfire catastrophe (over 10 Mha burned) in 2019-2020 (Bowman et al., 2021; Figure 4: area burned along the Australian eastern seaboard and southwest of Adelaide).

Prescribed burning (also called hazard reduction burning or planned burning) is a commonly used tool to manage bushfire risk, because it is a cost-effective method of reducing under-canopy fuel loads in savanna and dry Eucalypt forests. However, prescribed fires can also be a significant source of smoke. In southern Australia, population exposure to smoke can be compounded by the overlap of the prescribed burning season with the Southern Hemisphere autumn, when atmospheric ventilation rates are reduced, keeping smoke closer to the surface; wood combustion heaters add an additional source of smoke into the lower atmosphere.

The smoke hazards associated with bushfires and prescribed burning are well recognized in Australia (Horsley et al., 2018), and air pollution forecasting systems coupled with effective now-casting tools and population alert systems have been adopted by many environmental agencies in Australia's states and territories. In the following sections, we summarize three of the Australian smoke forecasting systems and frameworks: (1) the Air Quality Forecasting (AQFx) system, managed by the Bureau of Meteorology with a focus on forecasting smoke from prescribed burns in the state of Victoria (Figure 4); (2) the Coordinated Smoke Management System (CSMS), managed by the Tasmanian Forest Practices Authority for planned burn management in that state; and (3) the air quality forecasting system for the state of New South Wales (NSW) operated by the NSW Department of Planning, Industry and the Environment (DPIE).

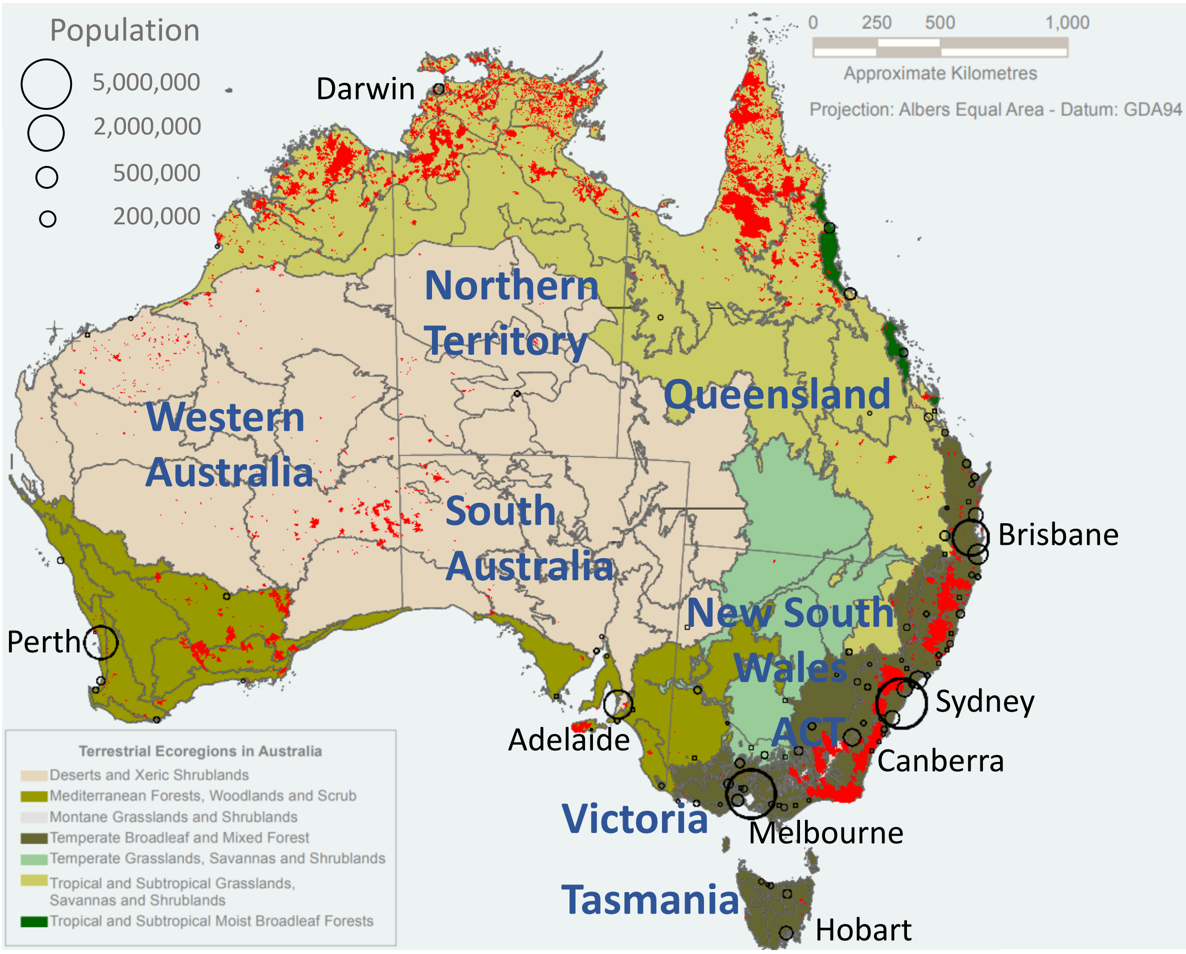


Figure 4: Map of Australia showing states and territories (ACT: Australian Capital Territory), capital cities, significant population centers, the major terrestrial ecoregions, and burned areas (red) for July 2019-March 2020. Data sources: The National Reserve System/Australia's ecoregions (https://www.environment.gov.au/land/nrs/science/ibra/australias-ecoregions); National Indicative Aggregated Fire Extent Datasets (https://www.environment.gov.au/fed/catalog/search/resource/details.page?uuid=%7B9ACDCB09-0364-4FE8-9459-2A56C792C743%7D); Australian Bureau of Statistics: regional population (https://www.abs.gov.au/statistics/people/population/regional-population/2019-20).

5.1 The Air Quality Forecasting System (AQFx)

AQFx was developed following a Victorian Royal Commission report (http://royalcommission.vic.gov.au/finaldocuments/summary/PF/VBRC_Summary_PF.pdf) into the Black Saturday fires, which swept through Victoria on 7 February 2009. The magnitude and intensity of the fires killed 173 people, far exceeding the loss of life from any prior bushfire. The Royal Commission recommended that the state of Victoria mandate and support a long-term program of prescribed burning based on an annual target of five per cent (minimum) of public land. The need to manage smoke exposure resulting from such an annual burn target was one of the drivers for the development of AQFx.

Funded by the Victorian Department of Environment, Land, Water and Planning (DELWP), AQFx was a collaboration between the Australian Bureau of Meteorology (BOM), the Commonwealth Science and Industrial Organization (CSIRO) and four Australian universities. The project was tasked with developing a system that could provide forecasted guidance on the fire weather outlook over a weekly planning cycle, as well as smoke transport forecasts for prescribed burns in the context of other existing sources of air pollution within the Victorian region over a 24- to 72-hour forecast period. The project (Cope et al., 2019) included construction of fine and coarse fuel layer data sets for Victoria (Volkova et al., 2018); modeling of fire propagation and smoke constituent emission factors in an outdoor Pyrotron (Sullivan et al., 2018); in situ observations of smoke emission factors for prescribed burns in dry Eucalypt forecasts (Reisen et al., 2018); adaptation, deployment, and verification of numerical forecasting tools; and training of Emergency Management Victoria personnel in the use of the system (e.g. https://delwp.publish.viostream.com/delwp-video-embed/media?v=ny1ykcsnp8oks6).

The AQFx framework generates three cascading time levels of weather and smoke forecasting output. Table 3 summarizes the AQFx technology and datasets, which are built around a suite of daily numerical meteorological forecast products generated by BOM using the Australian Community Climate and Earth-System Simulator (ACCESS). In Victoria and NSW, bushfire behavior is modeled using Phoenix Rapid Fire (Table 3), which is linked to fire agency fire locality data. Prescribed burn behavior (Victoria) is modeled using Phoenix Fire Flux (Table 3) and is linked to the DELWP daily schedule of prescribed burns. Satellite hotspot data are used to estimate the daily area burned by active fires in the other states and territories (Meyer et al., 2008). Smoke emissions from the flaming and smoldering components of an active fire are modeled using the CSIRO smoke emissions model (C-SEM; Table 3). Smoke plume rise, transport, and chemical transformation are modeled using the CSIRO chemical transport model (C-CTM; Table 3) operating in a forecast configuration (e.g. Table 12.7 of WMO (2020)); or with HYSPLIT for prescribed burn forecast outlooks of over 36 hours.

The three tiers of forecast products generated by the AQFx framework are as follows.

- Tier 1: Ensemble fire weather parameter forecasting using the ACCESS-G3 global ensemble forecasts (18 ensemble members; Table 3).
- Tier 2: Daily single deterministic 24- to 96-hour (depending upon model grid size; see below) forecasts for the Australian region, with a focus on Victoria (Figure 5a), available each morning by 0900 local time. Tier 2 is used to forecast total air pollution loading within an airshed, with a focus on PM2.5, PM10, and ozone; it includes active prescribed burns and bushfires, windblown dust, other natural sources, and anthropogenic sources.

- Tier 3: 24-hour forecasts of prescribed burn smoke (extendable to 96 hours using HYSPLIT). The Tier 3 forecasting cycle is coupled to the DELWP smoke management process. AQFx polls the schedule of candidate next-day prescribed burns by 1500 local time. Forecasts of next-day smoke exposure for individually tracked fires are provided to DELWP by 1700 local time (Figure 5b,c). Candidate burns then selected for ignition are added to the Tier 2 forecast, which is run overnight (Figure 5d). On the morning of ignition, Tier 2 and Tier 3 forecasts can be combined to give a two-member ensemble forced by different meteorological forecasts (Figure 5).

The tiered forecasting approach is a compromise between the treatment of forecast uncertainty for extended outlooks (5 days, and thus the need for an ensemble approach), and the computational demands of numerical air quality forecasting over large, nested domains over a 24-hour (1-3 km model grid size) to 72-hour (9-27 km model grid size) outlook. BOM began experimental AQFx forecasts in January 2016 and upgraded AQFx to operational status for Victoria in 2017 and NSW in 2018. For examples of AQFx performance, see Cope (2018) and Cope et al. (2019).

5.1.1 Future plans

The southern hemisphere Australian 2019-2020 bushfire season was characterized by the greatest warming of Indian ocean sea surface temperatures on record, coupled with the northern movement of the belt of strong westerly winds surrounding Antarctica which decreased rainfall in SE Australia. These seasonal factors combined with a significant hydrological drought to generate extreme fire weather conditions across the continent. The national average Forest Fire Danger Index (FFDI) for spring 2019 was the highest on record, and high to extreme levels of FFDI extended through January 2020 in parts of South Australia, Victoria, and New South Wales (BOM, 2020a). These conditions led to an unprecedented bushfire season in eastern Australia (Bowman et al., 2021) from August 2019 to March 2020. Bushfires burned over 10 million Ha, including 18% of all Australian dry and wet Eucalyptus forest (Figure 4), resulting in the direct loss of life of 33 people and the estimated deaths of nearly one billion mammals, birds, and reptiles (Dickman & McDonald, 2020).

The most densely populated regions of Australia were exposed to significant concentrations of smoke for extended periods during the 2019-2020 bushfire season. Johnston et al. (2021) estimated that population exposure to PM2.5 from bushfire smoke caused more than 1,500 asthma emergency attendances, hospital admissions for over 2,000 respiratory and 1,100 cardiovascular conditions, and over 420 premature deaths. Total health costs were AU$1.95 billion, nearly an order of magnitude more than the median of the previous

19 bushfire seasons. Tier 2 AQFx forecasting capability was extensively used throughout the season and was provided on request to fire agencies and environment departments for all impacted states and territories.

A Royal Commission into National Natural Disaster Arrangements (https://naturaldisaster.royalcommission.gov.au/) undertook an extensive investigation into the 2019-2020 bushfires (and other natural disasters) and was tasked to provide recommendations to optimize Australia's national natural disaster coordination. Of note is the commission's Recommendation 14.2: "Australian, state and territory governments should develop national air quality forecasting capabilities, which include broad coverage of population centers and apply to smoke and other airborne pollutants, such as dust and pollen, to predict plume behavior."

An outcome of Recommendation 14.2 is that AQFx is being expanded to generate national bushfire smoke forecasts. The time frame to undertake this work is tight, with an initial prototype system to be deployed before the 2021-2022 Australian bushfire season. A list of tasks includes the following.

- Review AQFx forecasting capability for the 2019-2020 bushfire season.
- Engage closely with the national air quality community, encouraging state and territory government practitioners to provide guidance and feedback during the prototype system development.
- Deploy a nationally consistent fire behavior forecasting methodology based on the Australian Fire Danger Rating System (AFDRS) national fuel layer (https://www.afac.com.au/initiative/afdrs) and the SPARK fire propagation platform (https://research.csiro.au/spark/).
- Deploy an assimilation package that will leverage existing (assimilated) global chemical atmosphere forecasts at the national scale, and a local/regional scheme that constrains wind-blown dust and smoke emissions (e.g. Dai et al., 2019).
- Deploy a forecast-data blending scheme (e.g. Majumder et al., 2021) for the near-real time analysis and dissemination of spatial surface-layer PM2.5 concentration fields through government-facing and public cloud-based apps (Campbell et al., 2020; Williamson & Lucani, 2020).
- In support of the above, deploy a low-cost fine particle sensor (https://ecos.csiro.au/smog/) network, with a focus on improving coverage in existing smoke-prone but sparsely monitored regions.

A review of the performance of the AQFx prototype forecasting system will be undertaken at the end of the 2021-2022 bushfire season, and system components will be further refined as required. Modules from the AQFx prototype will then become available for incorporation into the BOM operational system.

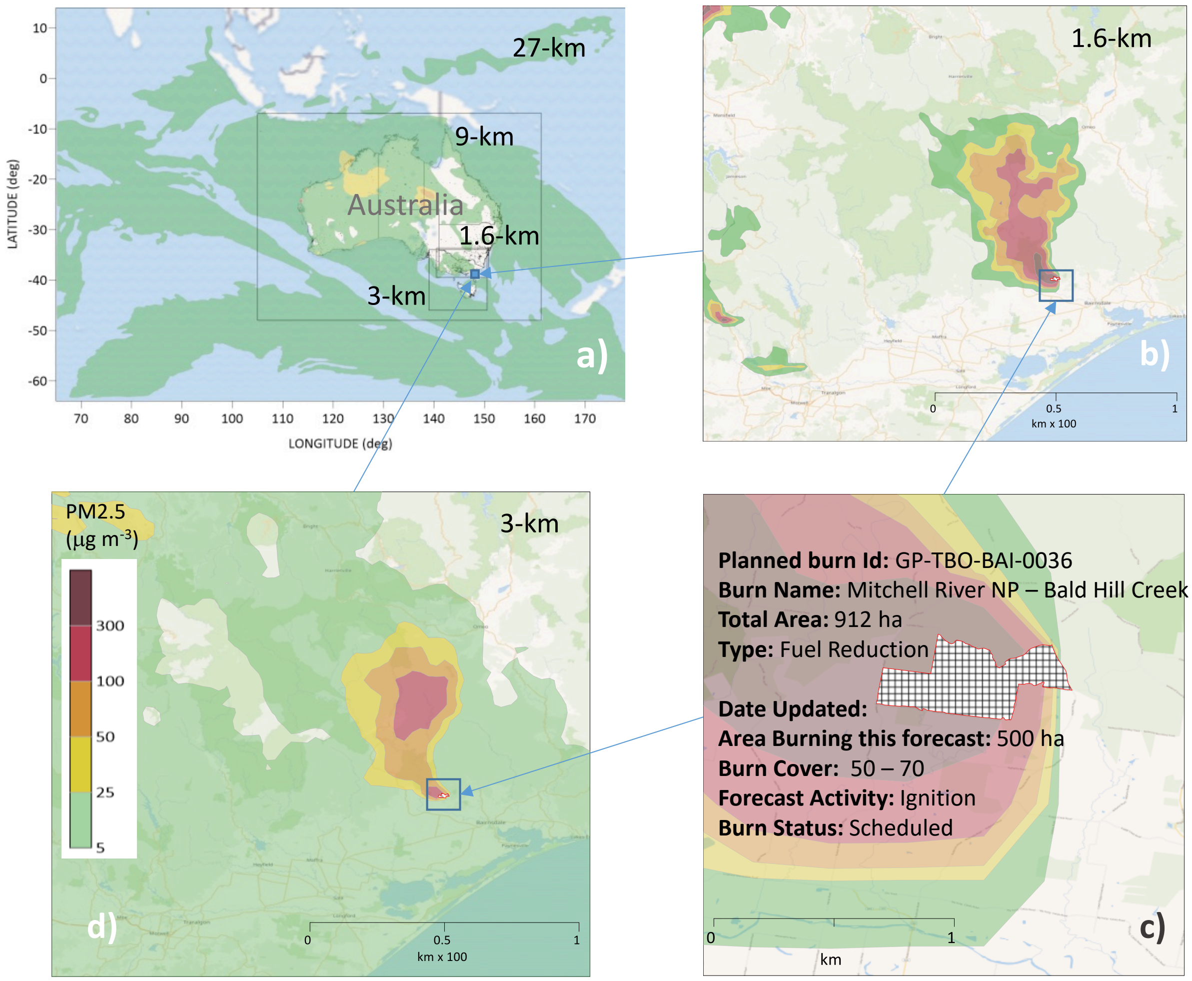


Figure 5. (a) Forecast of near-surface PM2.5 for 1000 UTC 31 March 2021. The three domains (27-km, 9-km, and 3-km model grid size; 19 vertical levels) used for Tier 2 forecasting (all air pollution sources) for a 24- to 72-hour outlook. The 3-km domain here is configured to provide high-resolution forecasts for the Victoria and Tasmania in southeastern Australia. The fourth domain (1.6-km) is used for prescribed burn forecasting (tracer mode configuration), shown here for Victoria. (b) Prescribed burn forecast (1.6-km domain) for a small region in southeast Victoria for the same date and time. (c) The characteristics of the prescribed burn in (b), including a shapefile of the proposed burn area. (d) The full chemical forecast for the same time. The PM2.5 forecasts in (b) and (d) differ because of the domain resolution differences, the inclusion of other particle sources (including secondary aerosols) in the chemical forecast (d), and because the 3-km forecast is undertaken with more recent meteorological forecast (12 UTC) than the tracer forecast (00 UTC).

Table 3. Summary of the technologies and data used by the Australia AQFx air quality forecasting framework.

Technology/data	Description	Australia AQFx application
Meteorological forecasts	Bureau of Meteorology ACCESS forecasting products. current generation ASP3- http://www.bom.gov.au/australia/charts/bulletins/opsbull_G3GE3_external_v3.pdf Global ensemble. 33 km model grid size; 70 vert levels; 18 members 10-day forecasts Global deterministic, 12 km model grid size; 70 vert levels 10-day forecast City deterministic; 1.5km model grid size; 80 vert levels; hourly data assimilation. Graphical Forecast Editor (GFE)- bias corrected surface weather	Tier 1: Global ensemble for the calculation of fire weather and fire danger parameters. Tier 2: Global deterministic used for C-CTM (see below) 27 km and 9 km domains. City deterministic used for C-CTM 3 km domains. Tier 3: City deterministic for C-CTM 1.6 km domains. Global and City deterministic for HYSPLIT (see below). GFE is used to drive Phoenix Rapid Fire and Phoenix Fire Flux (see below).
Anthropogenic air pollution emissions	State EPA air emission inventories. For example- https://www.epa.nsw.gov.au/your-environment/air/air-emissions-inventory.	Tier 2. Australia-wide anthropogenic emissions are estimated using emission factors derived from the NSW inventory and population-based spatial weighting. Bottom-up inventories from the state EPAs take precedence where available.
Natural and geogenic emissions	Emissions of dust, sea salt, biogenic volatile organic compounds, and soil nitrogen compounds	Tier 2. Calculated inline during the CTM integration (e.g. Emmerson et al. (2018)).
Bushfire fire propagation	Phoenix Rapid Fire. (https://firepredictions.atlassian.net/wiki/spaces/PH/pages/405176343/PHOENIX%2BTechnical%2BReference%2BGuide	Tier 2 forecasting for Victoria and New South Wales.
Phoenix Fire Flux	Phoenix Fire Flux (Cope et al., 2019, pp. 36-38; Appendix C)	Tier 2, Tier 3 for Victoria.
Smoke emissions	C-SEM smoke emissions model (Cope et al., 2019, pp. 40-42)	Tier 2, Tier 3 for Victoria.
Chemical Transport model	CSIRO chemical transport model (C-CTM; Guérette et al., 2020; Lawson et al., 2017)	Tier 2, Tier 3. See Table 12.1 of WMO ETR-26 (https://library.wmo.int/index.php?lvl=serie_see&id=240) for a summary of a specific a C-CTM forecasting configuration.
HYSPLIT	Stein et al. (2015).	Tier 3. HYSPLIT is used, on request, for prescribed burn smoke transport forecasts with an outlook extending beyond 48 hours. Tracer transport with unit emission rates.
AQVx	AQFx visualisation system. (Williamson & Lucani, 2020).	Cloud-based app used to visualise AQFx near real time forecast, observations, satellite data, and contextual ground-based data.

5.2 Tasmania's Coordinated Smoke Management System (CSMS)

Tasmania, the island state of Australia, is located in temperate latitudes and has a relatively small and distributed human population of 500,000. Planned burning is conducted by organizations such as forestry companies (post-harvest regeneration burning), the state Parks and Wildlife Service (land management burns), the Tasmania Fire Service (hazard reduction burns), councils, and private land holders (agricultural and hazard reduction burning). Burning is mostly conducted in autumn and spring. Tasmania also has a large tourism base and a well developed wine industry. Smoke from planned burning can be a problem for tourist operators and vintners as well as the general community. To address this concern, the Tasmanian Forest Practices Authority (FPA) and Environmental Protection Authority (EPA) Tasmania created the Coordinated Smoke Management System (CSMS) and the Base-Line Air Network of EPA Tasmania (BLANkET) real-time ambient air monitoring network (Figure 6).

The CSMS strategy limits the amount of smoke produced in a given area of Tasmania on a given day. Under the CSMS, Tasmania is divided into airsheds (e.g. regions; Figure 6). Each airshed has a maximum daily burn-unit allowance. Burners wishing to conduct a burn on a given day place a bid to burn a certain number of burn-units by 0730 local time via a web server. The server then calculates a burn-unit allocation (or daily quota) in the relevant airshed. The daily allowance in each airshed varies with the forecast ventilation index and (if present) the inversion layer height for that day and region from Australia's Bureau of Meteorology forecast system. The number of applicable burn-units for a given burn is calculated based on the burn area and fuel type, as specified in a guidance document. Software on the web server allocates units to the burners daily. If the total number of units requested for an airshed exceeds the daily quota, all bids for that airshed are reduced proportionally to the allowed total. On days when very poor dispersion is forecast (low ventilation index), the quota may be zero.

Analysis of the air quality data from the expanded network has identified valuable information on smoke movement and dispersal in Tasmania and circumstances where smoke may affect communities. For example, katabatic winds (cold air drainage) may transport smoke from fires smouldering overnight to population centers, which can be a significant mechanism for smoke exposure in many areas of Tasmania. The katabatic winds tend to be more prominent during regionally calm conditions. Information of this nature is provided to burners and forms part of the documented guidance principles. Another feature of the system is the designation of 'no burn days': if the measured PM2.5 concentration in an airshed at 0900 local time exceeds 25 μg/m^3, the default is that no further burning takes place in that airshed on that day. This rule has significantly reduced the severity and duration of smoke impacts on populated areas, particularly in the Huon Valley south of Hobart.

Although the CSMS is a voluntary framework, it has been adopted by the major burn agencies and organizations in Tasmania as best-practice smoke management. A steering committee chaired by the FPA with membership from the burners, EPA Tasmania, and the Department of Health meets to review burning seasons and to consider whether revisions are needed. Adoption of the CSMS, and the establishment of the expanded air monitoring network, have provided a sound basis for improving planned-burn smoke management in Tasmania. Since the CSMS began, the number of public complaints about planned-burn smoke received by EPA Tasmania have significantly decreased and for some areas of the state, measured peak smoke levels in autumn have also decreased. The CSMS is likely to have played a significant role in these changes.

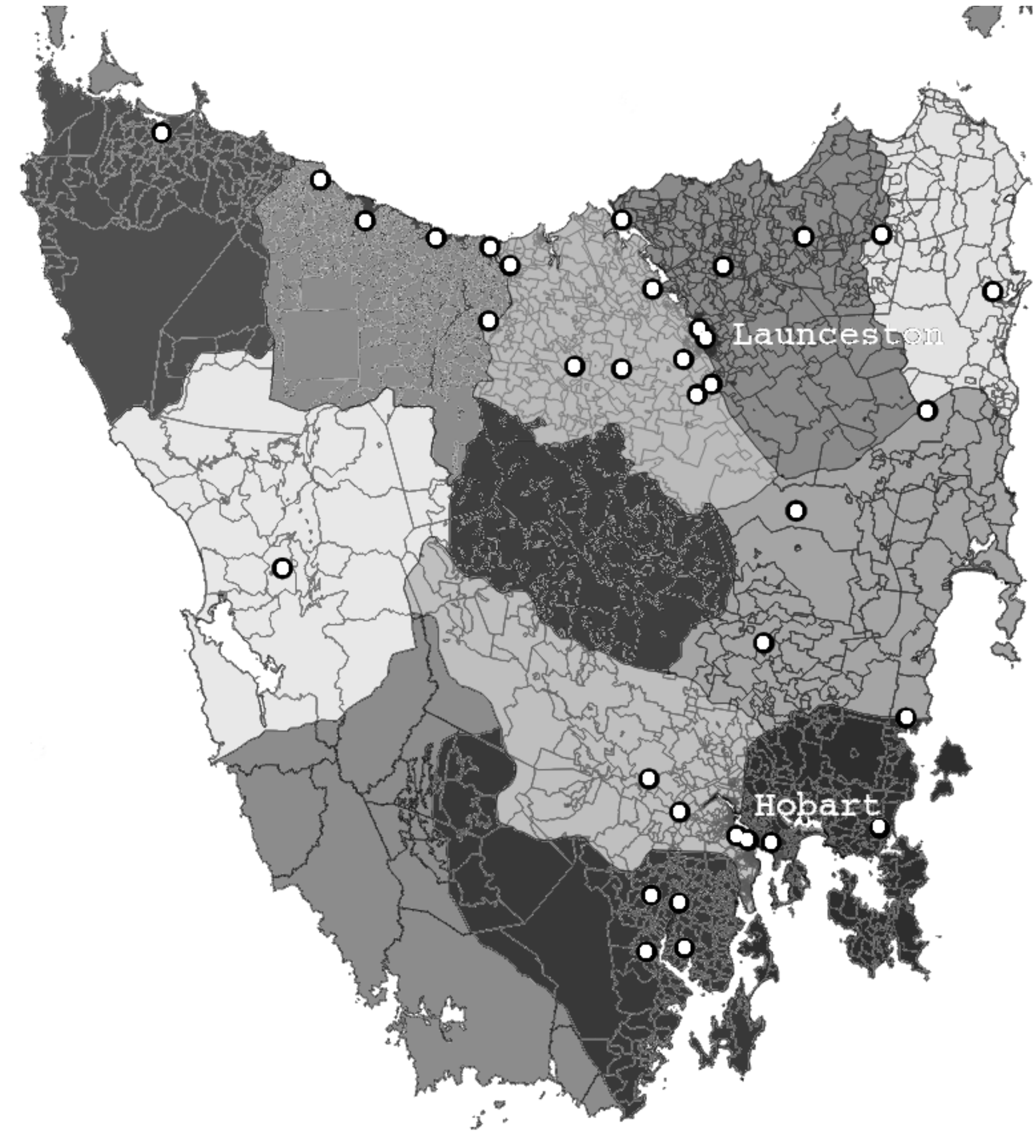


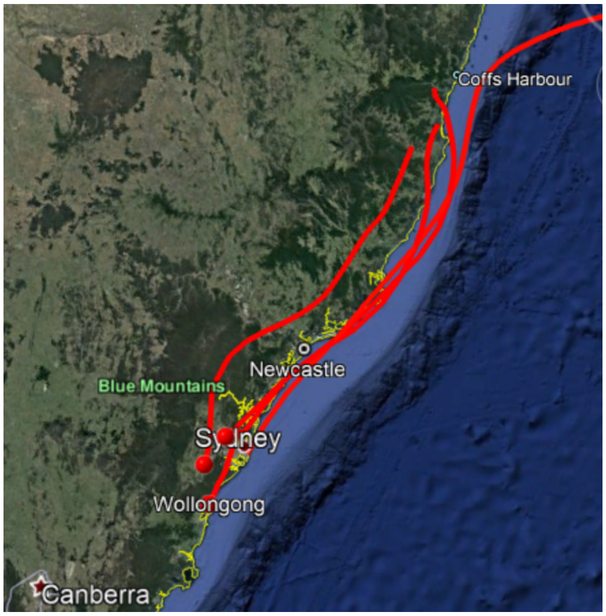
Figure 6: Map of Tasmania. Colored regions: Coordinated Smoke Management System (CSMS) airsheds. Black circles: locations on EPA Tasmania's real-time air monitoring stations. Monitors are located primarily in towns and larger population centers.

5.3 New South Wales (NSW) Air Quality Modeling System

The New South Wales Air Quality Forecast Framework was established in 2015 (Jiang et al., 2015) with the goal to produce accurate early warnings about when and where ambient air pollutant concentrations may exceed recommended levels. The NSW Department of Planning, Industry and Environment (NSW DPIE) operates an air quality modelling system that provides 72-hour forecasts of air pollutant concentrations for the Greater Metropolitan Region of New South Wales. Air quality alerts are issued on days when pollution levels are forecast to be unhealthy or worse. The system consists of two modelling systems. The first is a trajectory and dispersion system using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT; Stein et al., 2015) developed by the NOAA and tailored for NSW, known as "HYSPLIT in NSW" (Lisa Tzu-Chi Chang et al., 2021). The second is an air quality modeling system, which includes the coupled Conformal Cubic Atmospheric Model and Chemical Transport Model system (L. T.-C. Chang et al., 2018), with meteorology from the Australian Community Climate and Earth-System Simulator (ACCESS) Numerical Weather Prediction (NWP) system (http://www.bom.gov.au/nwp/doc/access/NWPData.shtml).

HYSPLIT in NSW is driven by high spatial resolution (4-12 km model grid cell size) ACCESS regional weather forecast data and streamlined to provide automated atmospheric trajectories and dispersion forecasts. It has been operational since July 2019 and provides forecasts twice daily. The system driven by the higher-resolution meteorological data (e.g. 4 km grids) improves certainty when identifying areas that may be affected by smoke from bushfires (Watt et al., 2017), regional dust storms, and industrial incidents. Figure 7a shows the 24-hour back-trajectories starting at 1000 local time on 29 December 2019 from locations in Sydney and Wollongong. The back-trajectories indicate that these air parcels travelled through major smoke plumes over eastern NSW (Figure 7b) in the 24 hours before they arrived Sydney. During the 2019-2020 bushfire season, routine evaluations of the HYSPLIT in NSW trajectories was conducted by visually comparing smoke plumes tracked by Moderate Resolution Imaging Spectroradiometer (MODIS) Corrected Reflectance imagery.

The numerical regional airshed model consists of a meteorological module, emission modules, and a chemical transport module. It was configured by the NSW DPIE to run twice a day since 2018 to support the routine daily air quality forecasts. The NSW Greater Metropolitan Region Air Emissions Inventory documents anthropogenic emissions used in the regional airshed modelling; natural sources, including wind-blown dust, sea salt, and biogenic emissions, are estimated in-line within the model. Emissions of pollutant species from wildfires and hazard reduction burns (HRBs) are estimated by the Smoke Emission Module (Monk et al., 2019) running outside of the airshed modelling. Figure 8 gives an example of daily numerical modelling forecasts, showing hourly PM2.5 concentrations on a 1-km spatial resolution domain at 1000 local time on 29 December 2019. Routine evaluation is conducted with monitoring data from the comprehensive Air Quality Monitoring Network operated by the NSW DPIE.



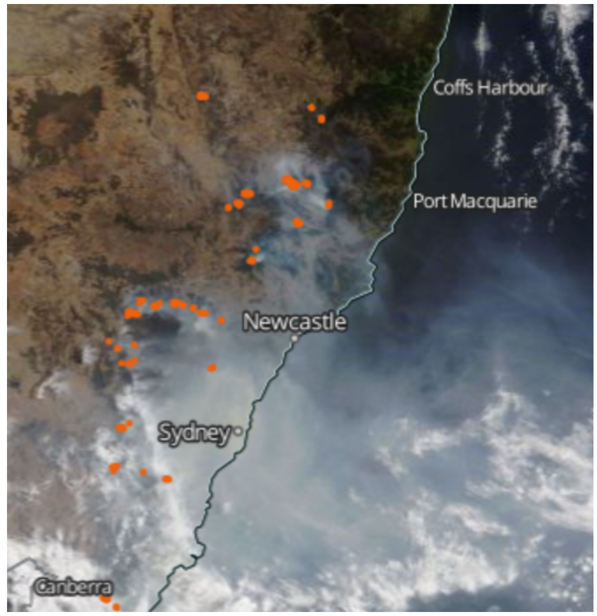


Figure 7. (a) HYSPLIT in NSW 24-hour back-trajectories starting at 1000 29 December 2019 from locations in Sydney and Wollongong; (b) Terra/MODIS satellite imagery on the same day showing hot spots (fires) and smoke plumes on the northern coast and in eastern New South Wales.

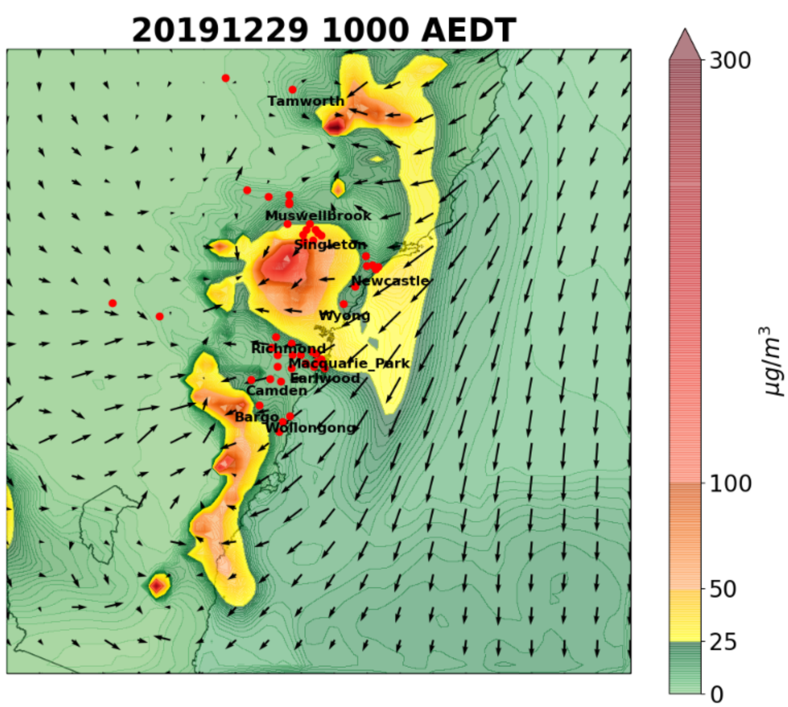


Figure 8. Examples of the numerical modelling forecasting products from the New South Wales Department of Planning, Industry and Environment (NSW-DPIE), showing the hourly PM2.5 concentrations (μg/m^3) and surface winds valid at 1000 on 29 December 2019 for the 1-km spatial resolution domain.

6. World Meteorological Organization (WMO) Vegetation Fire and Smoke Pollution Warning Advisory and Assessment System (VFSP-WAS)

The 18th World Meteorological Congress in June 2019 endorsed an ambitious plan to advance the integration of weather, climate, water, and environmental applications and services for health, as well as to work closely with the World Health Organization (WHO) to reduce risks to human health. Populations both near and downwind of wildfires need better warnings about serious threats posed by both the fires themselves and related air quality risk levels. The World Meteorological Organization (WMO) has responded to urgent requests for assistance in several impacted regions by initiating a Vegetation Fire and Smoke Pollution Warning Advisory and Assessment System (VFSP-WAS) (https://community.wmo.int/activity-areas/gaw/science/modelling-applications/vfsp-was). The VFSP-WAS provides guidance to address both smoke and fire danger and proposes to support the potential foundation of regional centers (WMO, 2018).

Figure 9 shows the functional organization of a VFSP-WAS, including the interactions between the system's components and activities. The proposed warning and advisory system builds upon a number of comparable initiatives, such as CAMS, the WMO Regional Specialized Meteorological Centers (RSMCs), the Association of Southeast Asian Nations (ASEAN) Specialised Meteorological Centre (ASMC) in Singapore, the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) with regional centers in Barcelona and in Beijing, the Global Air Quality Forecasting and Information System (GAFIS, https://community.wmo.int/activity-areas/gaw/science-for-services/gafis), and the International Cooperation for Aerosol Prediction (ICAP).

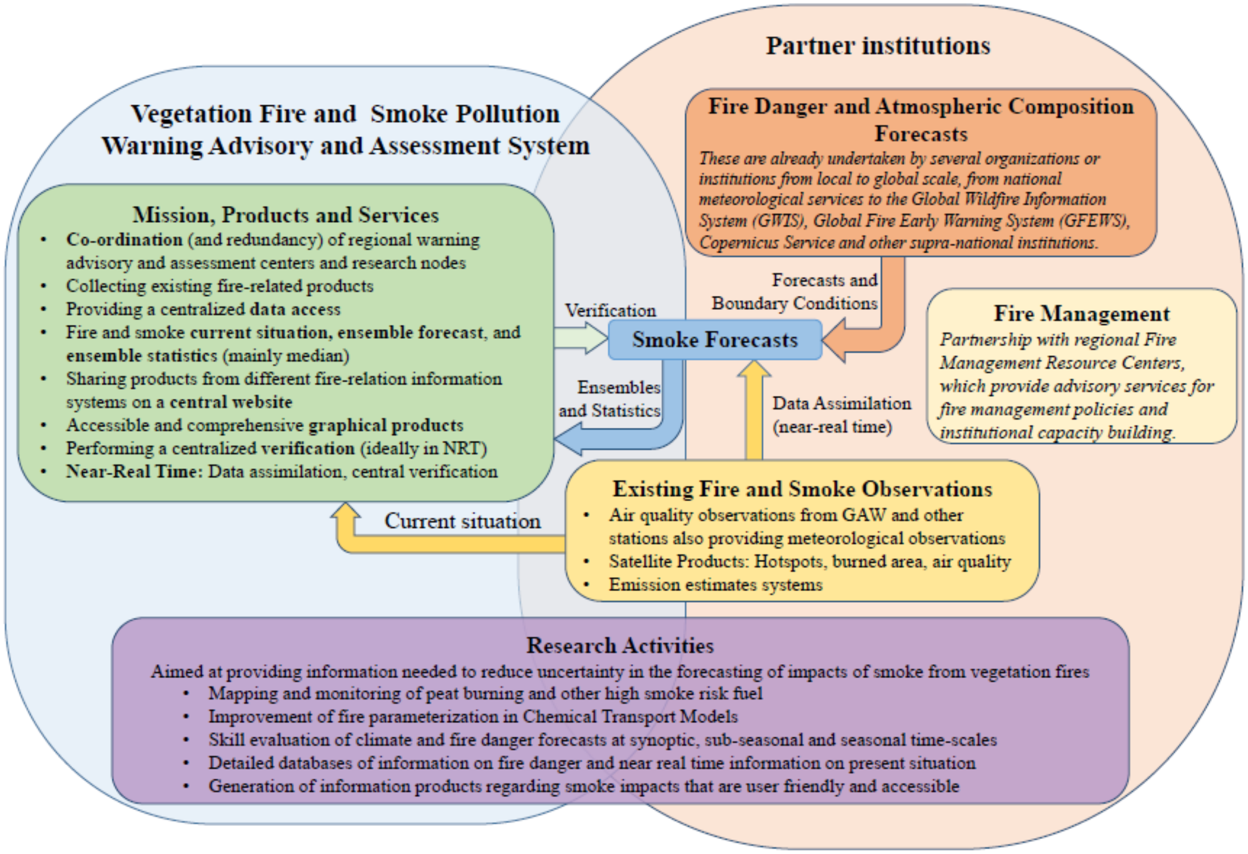


Figure 9 – Overview of a Vegetation Fire and Smoke Pollution Warning Advisory and Assessment System (VFSP-WAS), including its mission, products and services; research activities; smoke observations and forecasts; and connections with fire management centers and other potential end users.

At the regional level, VFSP-WAS is organized as a federation of regional partners contributing to Nodes and realized through Regional VFSP-WAS Centers (VFSP-WAC) (Baklanov et al., 2021; WMO, 2018; Figure 10). Each potential Node is an open federation of partners from interested countries in the region, with equal votes of each partner. A federated approach allows flexibility, growth, and evolution, while preserving the autonomy of individual institutions. Regional Nodes can involve the cooperation of, and provide benefits to, a variety of participants (e.g. universities, research organizations, meteorological services, emergency management bodies, health organizations). The organization of research and development and forecasting activities at a Node is defined and led by a Regional Steering Group and practically realized by the Regional VFSP-WAC. The VFSP-WAC can be hosted by one or several countries/organizations of the region, based on agreement of the Node members, and it focuses on technical realization of the Regional VFSP-WAS. A scheme of the governance structure of Regional VFSP-WAC is presented in Figure 10. Regional VFSP-WAC provide information, including warnings and advice, to support fire and emergency management to help partners react appropriately to harmful fire episodes. Because fire and smoke predictions still need considerable development, these centers also aim to bridge gaps between research and operational work.

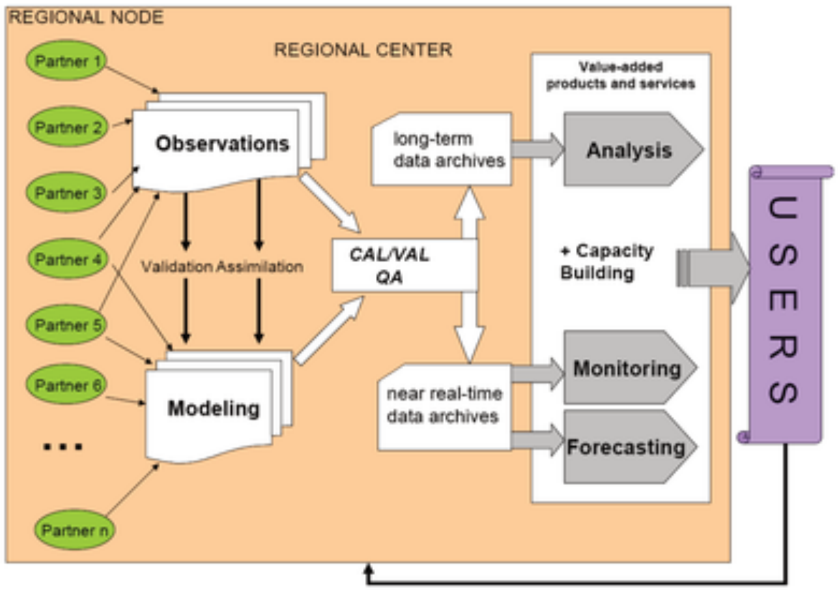


Figure 10 – Scheme of the governance structure of a Regional Node and Fire and Smoke Pollution Warning Advisory and Assessment Center (VFSP-WAC).

The first research and development phase of the VFSP-WAS was launched in 2018. Before an operational Regional Specialized Meteorological Centre (RSMC) for VFSP-WAS can be approved, the center is evaluated by WMO Technical Commissions and further included in the Global Data-Processing and Forecasting System (GDPFS) (WMO, 2017). Several regions (North America, Southeast Asia, Latin America, and Northern Europe) are interested or have demonstrated infrastructure necessary to host such Regional Centers for the realization of VFSP-WAS, and they also have good experience and research.

This section describes the first and most established two VFSP-WACs on the research and advanced development stage, which are recommended as prototypes for Regional VFSP-WACs. (1) In Singapore, regional models are run and forecasts from various centers are collated to produce multi-model ensemble smoke forecasts for Southeast Asia. (2) In North America, Environmental and Climate Change Canada (ECCC) in Canada has established a demonstration VFSP-WAS center. Both centers produce ensemble particulate matter and AOD forecast products, with real-time evaluation either functioning or in development. They also include fire weather or fire risk forecast products as well as a section on current conditions with applicable observational data.

6.1 Singapore VFSP-WAS regional center for Southeast Asia

The first regional VFSP-WAC is hosted by ASMC for Southeast Asia. ASMC operates under the Meteorological Service Singapore (MSS). It was designated in 1997 as the official ASEAN center to monitor fires and transboundary smoke haze in Southeast Asia (Singapore, 1997). ASMC provides information on regional weather and haze, and issues alerts when biomass burning smoke is expected to affect any ASEAN country. ASMC also serves as technical advisor for ASEAN committees on transboundary haze and conducts capability development programs for regional users in environment, meteorological, and related agencies.

The Southeast Asia VFSP-WAC was established based on the experience of the WMO SDS-WAS (https://sds-was.aemet.es/) and ICAP, with collaboration from regional and global partners providing relevant products and services. In 2019, a pilot website for the Southeast Asia VFSP-WAS was launched in research and development phase to establish a multi-model ensemble with near-real-time forecast evaluation. In 2021, an upgraded version of this website (https://www.mss-int.sg/vfsp-was/) was deployed with a suite of enhancements, including longer-term evaluation metrics, observations, and fire risk products.

The Southeast Asia VFSP-WAC website also includes a review of the current weather and smoke haze situation, as well as a short-term outlook issued by ASMC. Three categories of products are on the website: forecasts (including performance evaluation), observations, and fire risk products.

6.1.1 Ensemble particulate matter and AOD forecast products

The VFSP-WAS multi-model ensemble includes five global models: ECMWF-CAMS (Europe), JMA MASINGAR (Japan), NASA GEOS (USA), NOAA GEFS-Aerosols (USA), and FMI SILAM (Finland). It also includes one regional model, the MSS-United Kingdom Meteorological Office Numerical Atmospheric-dispersion Modelling Environment (MSS-UKMO NAME) model. The forecast products include the ensemble and member predictions of smoke aerosol optical depth (AOD) and surface concentrations of PM10 and PM2.5. Regional weather forecast information includes sub-seasonal outlooks of rainfall and temperature issued by ASMC for Southeast Asia and NWP forecasts of winds at various height levels.

The VFSP-WAC retrieves available forecasts at 00 and 12 UTC from its partners and represents them over a regional domain covering major burning areas and smoke transport pathways at a common grid resolution of 0.5 degree x 0.5 degree. The ensemble and member forecasts are provided at 3-hour intervals up to 48 hours ahead. Figure 11 shows example products from the multi-model ensemble median forecast of smoke AOD and PM2.5 surface concentration. Two products describe product centrality (multi-model median, mean) and two describe product spread (standard deviation, range of variation). The ensemble mean and standard deviation forecast products are also compared to ICAP products derived for the region. The ICAP multi-model ensemble (Sessions et al., 2015; Xian et al., 2019) functions as a benchmark for the VFSP-WAC ensemble air quality forecast.

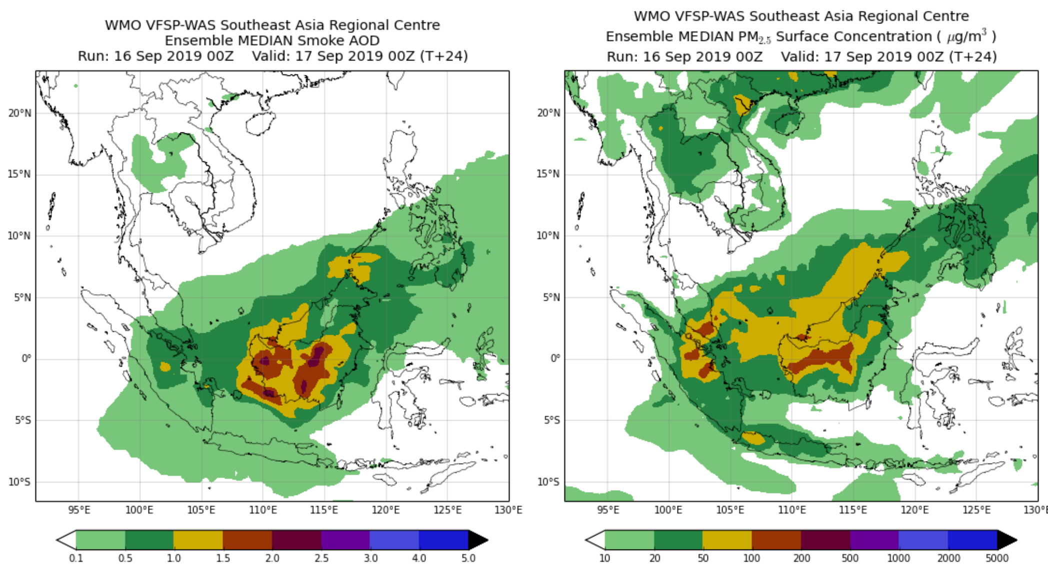


Figure 11. Example of Southeast Asia VFSP-WAC multi-model ensemble median 1-day forecast of smoke AOD (left) and PM2.5 surface concentration (right) for Southeast Asia in September 2019.

The MSS-UKMO NAME (Hansen et al., 2019; Hertwig et al., 2015) is the only regional and Lagrangian-based model in the ensemble. Fire radiative power (FRP) and smoke injection height products are obtained from CAMS-GFAS. The FRP products are subsequently applied over a high-resolution landcover and peatland map (Miettinen et al., 2012), which provides detailed information of fuel loading in Southeast Asia (Hertwig et al., 2015), thus allowing the derivation of smoke emissions calibrated for the region. Peatland burning is an important source of smoke emissions: about 250,000 km^2 of peatlands (56% of total tropical peatland) are in Southeast Asia, containing 70 Gt of carbon (i.e. 77% of tropical peat carbon and 11% of the world's total peat carbon pool; Page et al. (2011)). Other sources include three types of regional emissions: anthropogenic (MIX; M. Li et al., 2017), biogenic (CAMS-GLOB-BIO; Granier et al., 2019; Sindelarova et al., 2014), and shipping (EDGAR Version 4.3; Janssens-Maenhout et al., 2012). The NAME chemistry scheme includes the formation of secondary particulate matter; it is now used to generate realistic background pollutant levels, compared to earlier system versions described in Hertwig et al. (2015). In contrast to the other members in the ensemble, which employ more comprehensive aerosol optical models, NAME AOD forecasts are computed based on PM2.5 aerosol optical properties derived from an empirical study of biomass burning smoke over Singapore (S. Y. Lee et al., 2016).

6.1.2 Performance evaluation

Near real-time evaluations compare ensemble and member modelled AOD forecasts to NASA AERONET (Holben et al., 1998) Level 1.5 (Version 3) observations at 22 sites in the region; these are updated daily on the VFSP-WAC website (Figure 12). Clouds, especially cirrus clouds, are endemic in Southeast Asia and a source of potential bias in passive aerosol remote sensing datasets, such as AERONET (e.g. Chew et al., 2011). Thus, in addition to the standard AERONET cloud screening (Smirnov et al., 2000), a threshold of Angstrom exponent (440-870 nm) >0.75 is applied to screen AOD measurements for cloud contamination in the region (e.g. Chew et al., 2013; Salinas et al., 2009). Evaluation metrics (e.g. mean bias, root mean square error, correlation coefficient, fractional gross error) are also generated monthly, seasonally (3-month periods associated with regional burning processes and dominant monsoonal circulations) and annually; preliminary evaluation results are in Baklanov et al. (2021).

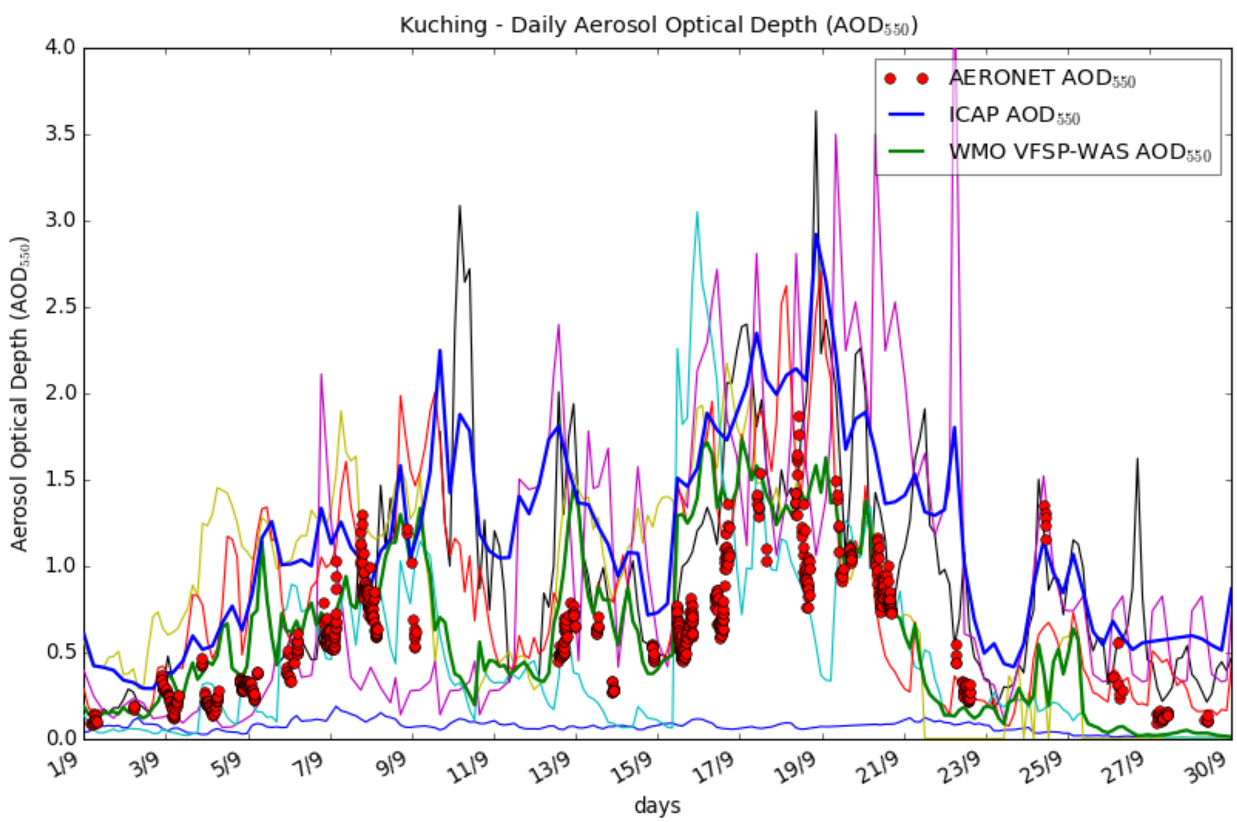


Figure 12. Near real-time Southeast Asia VFSP-WAC forecast evaluation over Kuching, East Malaysia during the

peak of fire activity in September 2019. Unlabeled colored lines represent six individual model members of the Southeast Asia VFSP-WAC ensemble.

6.1.3 Fire risk forecast products and Observational Datasets

Fire risk products are used to identify areas in the region at risk of fire based on prevailing weather conditions. The ASEAN Fire Danger Rating System (FDRS) and Global Fire Weather Database (GFWED) products are on the VFSP-WAC website. The ASEAN FDRS has been calibrated for Southeast Asia (De Groot et al., 2007) and is based on the Fire Weather Index (FWI) System developed by Canada. This product is produced daily by the Malaysian Meteorological Department. GFWED integrates different weather factors influencing the likelihood of a vegetation fire starting and spreading, and is also based on the FWI System (Field, 2020; Field et al., 2016).

Satellite images, weather information, and air quality station measurements are on the VFSP-WAC website. Satellite images include products from geostationary (Himawari-8) and polar-orbiting (NOAA20, SUOMI-NPP, AQUA, TERRA) satellites, such as true/false color and natural, fire temperature, and night images. The ground weather observation reports collected through the WMO Global Telecommunication System (GTS) are displayed on a map showing wind, visibility, and weather conditions. The website also displays available site measurements of surface particulate matter concentrations.

6.2 WMO VFSP-WAS regional center for North America

The government of Canada recently conducted several studies on wildfire pollution and associated human population exposure over North America (Matz et al., 2020; Munoz-Alpizar et al., 2017) using the operational ECCC air quality system, FireWork (J. Chen et al., 2019; Pavlovic et al., 2016; see Section 4). The importance of these consequences of wildfire pollution is a key driver for improving international collaboration in data sharing in support of wildfire preparedness and response.

In 2019, ECCC responded to the WMO's initiative and volunteered to create a North American (NA) Regional VFSP-WAC. This center began disseminating products in October 2020 (https://hpfx.collab.science.gc.ca/~svfs000/na-vfsp-was/public/dist/) and is the world's second Regional VFSP-WAC. The creation of the North American regional center involves close and effective collaboration with multiple national and international organizations (e.g. National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), US Forest Service

(USFS); National Resources Canada (NRCan); European Centre for Medium-Range Weather Forecasts (ECMWF); Japan Meteorological Agency (JMA); Finnish Meteorological Institute (FMI)). This partnership is essential for data collection and product tailoring for different national and international user needs.

The NA VFSP-WAC disseminates products related to smoke and fire, relying on contributions of participating agencies and ensembling of those products. The product suite includes information for smoke forecasts (PM2.5, PM10, AOD) and fire weather (the Canadian Fire Weather Index and monthly forecast estimates of precipitation and temperature anomalies). Current-condition products include maps of satellite-detected fire hot spots and fire danger estimates.

6.2.1 Ensemble particulate matter and AOD forecast products

The multi-model ensemble particulate matter forecast is based on six members. Two are regional: ECCC FireWork (Canada) and NOAA NCEP NAQFC (USA). Four are global: ECMWF CAMS-IFS (Europe), FMI SILAM (Finland), JMA MASINGAR (Japan), and NASA GEOS-FP (USA). In addition to the ensemble, forecasts from each member are presented separately. The common lead time for these ensemble members is 48 h, and the related forecast products will be updated once daily. These ensemble products are available over three North American windows: CONUS, Mexico, and Canada and Alaska (Figures 13a, 13b).

The ICAP Multi-Model Ensemble smoke AOD products are constructed from the following four aerosol forecast systems: ECMWF CAMS-IFS, NASA GEOS-FP, NRL NAAPS, and JMA MASINGAR. The ICAP AOD products are tailored over North America (Figure 13c) and, similar to the Singapore regional center, functions as a benchmark for the VFSP-WAC North America ensemble air quality forecast.

Performance evaluation for particulate matter concentration forecasts will be done with ground-level measurements from NA monitoring networks, using ECCC's Verification of Air QUality Models (VAQUM) System. VAQUM was developed in 2017 by ECCC in collaboration with ECMWF-Copernicus and NOAA and is used for operational AQ multi-model performance analysis over North America (Pavlovic et al., 2018).

6.2.2 Fire Weather forecast products

The Canadian FWI equation, provided by NRCan, calculates FWI over North America using ECCC's Operational Regional Deterministic Weather Forecasts, which is at 10-km horizontal grid spacing and is launched twice daily, producing 72-h lead-time forecasts. This FWI product has maps estimating the FWI 24, 48, and 72 hours into the future. These plots are still in development while partners discuss options for the provision of risk forecast products.

ECCC also produces sub-seasonal precipitation and temperature anomalies anomaly maps using Global Ensemble Prediction System (GEPS). These anomalies serve as an indicator for potential wildfires, especially when conditions are both drier than usual and warmer than usual. Forecasted anomalies are calculated from a 20-year climatology (1998-2017) of this prediction system obtained from a reanalysis. The monthly forecast is updated every Thursday and covers the subsequent 28 days (Figure 13d), starting on Monday.

6.2.3 Hotspots and fire danger maps over North America (current conditions)

Hotspot maps are available for the period covering the last 24 hours and previous 7-day period. This product provides information about current and most recent wildfire activity as detected by multiple satellites and processed throughout the CWFIS and GBBEPx systems. The fire danger maps are still in development and are now produced daily by combining the fire danger maps produced for Canada and Mexico through the Canadian Wildfire Information System (CWFIS) and from the US Wildland Fire Assessment System (WFAS). This map displays fire danger as classified by Canadian provincial, territorial, and US state fire management agencies.

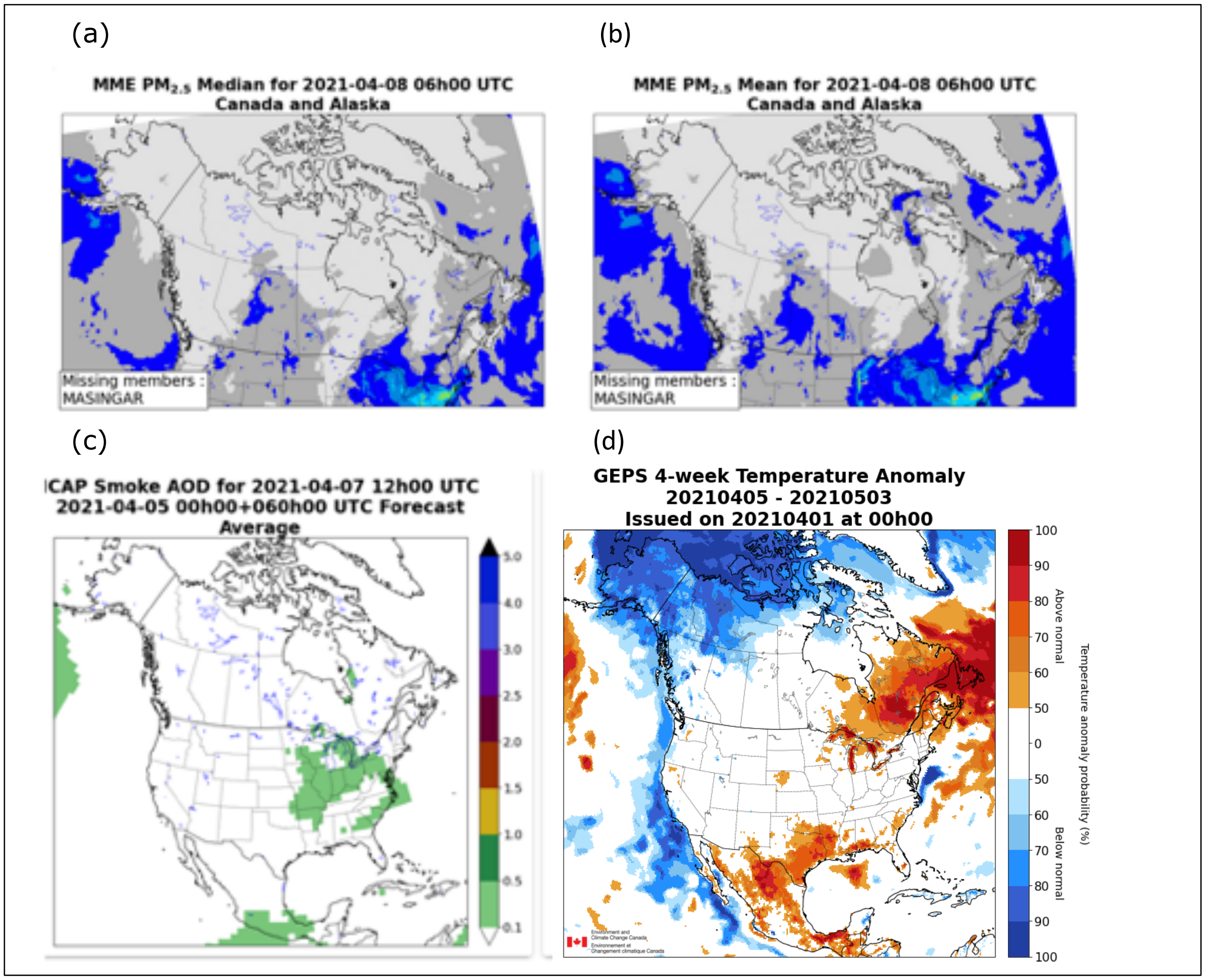


Figure 13: The multi-model ensemble (MME) (a) median and (b) mean $PM_{2.5}$ forecast over Canada and Alaska, valid at 2021-04-08 06 UTC, from the 2021-04-06 00 UTC initialized run. (c) The ICAP average Smoke AOD valid at 2021-04-07 12 UTC, from the 2021-04-05 06 UTC initialized run. (d) The forecasted temperature monthly anomaly issued on 2021-04-01 00 UTC. Data sources: NRCan-CWFIS (Canada/Mexico); USFS-WFAS (contiguous USA), and MesoWest (Alaska). Some of these maps are already disseminated by USFS-WFAS (US Forest Service – Wildland Fire Assessment System).

7. Summary

Here we profiled many of the global and regional smoke prediction systems currently operational or quasi-operational in real time or near-real time. It is not an exhaustive list of systems, but rather is a profile of many of the systems in use to give examples of the creativity and complexity needed to model the phenomenon of smoke. These systems rely on science and data discussed in the previous chapters of this book and reflect the different needs of agencies and regions, where the various systems are tailored to the best available science for a region and the specific challenges of the region. Smoke forecasting needs range from warning and informing the public about potential smoke impacts to planning burn activities for hazard reduction or resource benefit. Different agencies also have different mandates, and the lines blur between the missions of quasi-operational organizations (e.g. research institutions) and agencies with operational mandates.

The global smoke prediction systems are advanced, and many are self-organizing into the ICAP community with nine operational/research centers. One of ICAP's most significant contributions to the community is the development of the ICAP-Multi Model Ensemble which provides a testbed of probabilistic aerosol forecasts, helps to identify challenging areas for aerosol modeling, and forges valuable collaborations among forecast centers. The 11 regional air quality modeling systems in Europe utilize the global CAMS system, which is an ICAP participant, for initial and boundary conditions. Together, these 11 regional systems are another powerful ensemble. Biomass burning emissions are derived from satellite observation of fire radiative power by the GFAS and are used both in the global and regional systems. The regional models differ substantially in their chemical and aerosol schemes, deposition schemes, and the simulation of transport, diffusion, and planetary boundary layer processes. The 7 North American air quality and/or smoke predictions systems profiled are all independently developed by federal agencies or consortiums supporting University-based systems. Some simulate all pollutant sources in a chemical transport modeling system, while others only simulate smoke using a dispersion model or a chemical transport model (with coupled and offline cases). Biomass burning emissions are derived from ground-based fuel maps and consumption models or based on fire radiative power. Most of the systems are designed for wildfire conditions and are used by air quality and health agencies, but two systems are also designed specifically to aid prescribed fire operations, helping Land Managers determine burning opportunities based on air quality concerns. In Australia there are three smoke and air quality modeling systems addressing both wildfires (e.g. bushfires) and prescribed fire. The systems offer multiple modeling options, from chemical transport modeling of all sources including fires, to dispersion modeling of select prescribed burns to aid decision making. Finally, the World Meteorological Organization (WMO) effort brings together global and regional systems to form an ensemble to support countries with smoke issues and who lack resources.

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Disclaimer

The systems profiled in this chapter are continually under development as the science and technology of air quality and smoke forecasting improves. Therefore, the information provided here is a snapshot of the current state of these systems at the time of this writing. Further, this is not an exhaustive compilation of all systems globally, rather it represents many of the systems in use to give examples of the creativity and complexity needed to model the phenomenon of smoke.

Acronyms

ABI	Advanced Baseline Imager
ACCESS	Australian Community Climate and Earth-System Simulator
AFDRS	Australian Fire Danger Rating System
AIRPACT	Air Indicator Report for Public Access and Community Tracking
AQFx	Air Quality Forecasting
AQHI	Air Quality Health Index
AOD	Aerosol Optical Depth
ASEAN	Association of Southeast Asian Nations
ASMC	ASEAN Specialised Meteorological Centre
BB	Biomass Burning
BC	Black Carbon
BEIS	Biogenic Emission Inventory System
BLANkET	Base-Line Air Network of EPA Tasmania
BOM	Australian Bureau of Meteorology
BSC	BlueSky Canada
BSC	Barcelona Supercomputing Center, Spain
C-SEM	CSIRO smoke emissions model
CALIOP	Cloud-Aerosol Lidar and Infrared Pathfinder
CAMS	Copernicus Atmosphere Monitoring Service
CANSAC	California and Nevada Smoke and Air Committee
CFFEPS	Canadian Fire Emissions Prediction System
CMAQ	Community Multi-scale Air Quality
CO	Carbon Monoxide
CONUS	Continental US
CSIRO	Commonwealth Science and Industrial Organization
CSMS	Coordinated Smoke Management System
CWFIS	Canadian Wildland Fire Information System
DEASCO3	Deterministic and Empirical Assessment of Smoke's Contribution to Ozone Project
DEHM	Danish Eulerian Hemispheric Model
DELWP	Department of Environment, Land, Water and Planning (Victoria, Australia)
DPIE	Department of Planning, Industry and the Environment (NSW, Australia)

DRI	Desert Research Institute
ECCC	Environment and Climate Change Canada
ECMWF	European Centre for Medium-Range Weather Forecasts
EPA	Environmental Protection Agency
EMEP	European Monitoring and Evaluation Programme
ENEA	Energia Nucleare ed Energie Alternative, Italy
EURAD-IM	EURopean Air pollution Dispersion-Inverse Model
FBP	Fire Behaviour Prediction
FCCS	Fuel Characteristic Classification System
FEPS	Fire Emission Production Simulator
FFDI	Forest Fire Danger Index
FIS	Fire Information System
FLAMBE	Fire Locating And Modeling of Burning Emissions
FNMOC	Fleet Numerical Meteorology and Oceanography Center
FPA	Forest Practices Authority (Tasmania, Australia)
FRP	Fire Radiative Power
FMI	Finnish Meteorological Institute
FS	Forest Service
FWI	Fire Weather Index
GAFIS	Global Air Quality Forecasting and Information System
GBBEPx	Blended Global Biomass Burning Emissions Product
GDPFS	Global Data-Processing and Forecasting System
GEOS	Goddard Earth Observing System
GEFS	Global Ensemble Forecast System
GEM	Global Environmental Model
GFAS	Global Fire Assimilation System
GFWED	Global Fire Weather Database
GSL	US NOAA Global Systems Laboratory
HMS	Hazard Mapping System
HRRR	High Resolution Rapid Refresh
ICAP-MME	International Cooperative for Aerosol Prediction Multi-Model-Ensemble
IDEQ	Idaho Department of Environmental Quality
IEK	Institute of Energy and Climate Research, Germany
IEP-NRI	Institute of Environmental Protection – National Research Institute, Poland
INERIS	Institut National de l'Environnement Industriel et des Risques
IS4FIRES	Integrated Monitoring and Modelling System (IS) for wildland fires
IWFAQRP	Interagency Wildland Fire Air Quality Response Program
JMA	Japan Meteorological Agency
KNMI	Royal Netherlands Meteorological Institute
LAR	Laboratory for Atmospheric Research
MASINGAR	Model of Aerosol Species in the Global Atmosphere
MINNI	Italian National Integrated Assessment Model
MEGAN	Model of Emissions of Gases and Aerosols from Nature
MODIS	Moderate Resolution Imaging Spectroradiometer
MONARCH	Multiscale Online Nonhydrostatic AtmospheRe CHemistry model
MONCAGE	Météo France Modèle de Chimie Atmospherique à Grande Echelle
MOVES	MOtor Vehicle Emission Simulator, US EPA
MSC	Meteorological Service of Canada

MSS	Meteorological Service Singapore
MSS-UKMO NAME	MSS-United Kingdom Meteorological Office Numerical Atmospheric-dispersion Modelling Environment
NAAPS	Navy Aerosol Analysis and Prediction System
NAQFC	National Air Quality Forecast Capability
NEI	National Emission Inventory
NH3	Ammonia
NOAA	National Oceanic and Atmospheric Administration
NOX	Oxides of Nitrogen
NRCan	National Resources Canada
NRL	Naval Research Laboratory
NSW	New South Wales
NW-AIRQUEST	Northwest International Air Quality Environmental Science and Technology
NWP	Numerical Weather Prediction
O3	Ozone
OC	Organic Carbon
OM	Organic Matter
OMI	Ozone Monitoring Instrument
PBL	Planetary Boundary Layer
PM2.5	Particulate matter with aerodynamic diameter < 2.5 micrometers
PM10	Particulate matter with aerodynamic diameter < 10 micrometers
PMAp	Polar Multi-Sensor Aerosol product
PyroCB	Pyrocumulonimbus
QFED	Quick Fire Emissions Dataset
RAQDPS-FW	Regional Air Quality Deterministic Prediction System with Near-Real-Time Wildfire Emissions
RAP	Rapid Refresh
RSMC	Regional Specialized Meteorological Centers (WMO)
SDS-WAS	Sand and Dust Storm Warning Advisory and Assessment System
SILAM S	ystem for Integrated modeling of Atmospheric coMposition
SMHI	the Swedish Meteorological and Hydrological Institute
SO2	Sulfur Dioxide
SMARTFIRE v2 (SF2)	Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation
TNO	The Netherlands Organization for applied scientific research
UBC	University of British Columbia
UKMO	UK Met Office
UofA	University of Arizona
USDA	US Department of Agriculture
UW	University of Washington
VAQUM	ECCC's Verification of Air QUality Models
VFSP-WAC	Regional VFSP-WAS Centers
VFSP-WAS	Vegetation Fire and Smoke Pollution Warning Advisory and Assessment System
VIIRS	Visible Infrared Imaging Radiometer Suite
VOC	Volatile Organic Compounds
WACCM	Whole Atmosphere Community Climate Model
WFRT	Weather Forecast Research Team
WRAP	Western Regional Air Partnership
WMO	World Meteorological Organization

WRF	Weather Research Forecasting Model
WSU	Washington State University

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