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Chapter 22

Regional Real-Time Smoke Prediction Systems

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Abstract

Several real-time smoke prediction systems have been developed worldwide to help land managers, farmers, and air quality regulators balance land management needs against smoke impacts. Profiled here are four systems that are currently operational for regional domains for North America and Australia, providing forecasts to a well-developed user community. The systems link fire activity data, fuels information, and consumption and emissions models, with weather forecasts and dispersion models to produce a prediction of smoke concentrations from prescribed fires, wildfires, or agricultural fires across a region. The USDA Forest Service's BlueSky system is operational for regional domains across the United States and obtains prescribed burn information and wildfire information from databases compiled by various agencies along with satellite fire detections. The U.S. National Oceanic and Atmospheric Administration (NOAA) smoke prediction system is initialized with satellite fire detections and is operational across North America. Washington State University's ClearSky agricultural smoke prediction system is operational in the states of Idaho and Washington, and burn location information is input via a secure Web site by regulators in those states. The Australian Bureau of Meteorology smoke prediction system is operational for regional domains across Australia for wildfires and prescribed burning. Operational uses of these systems are emphasized as well as the approaches to evaluate their performance given the uncertainties associated with each system's subcomponents. These real-time smoke prediction systems

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are providing a point of interagency understanding between land managers and air regulators from which to negotiate the conflicting needs of ecological fire use while minimizing air quality health impacts.

22.1. Introduction

Smoke from fire is a local, regional, national, and often international issue. Large wildfires cause air quality impacts that are detectable on continental scales and beyond. Because fire is a natural and often integral part of many ecosystems, it is necessary for continued ecosystem health and maintenance. In the United States, prescribed fire use is increasing in order to counteract a history of fire suppression that has left many forests susceptible to catastrophic wildfires. Meanwhile wheat stubble burning and grass seed burning are typical practices in many farming communities. Many of these burning activities occur at rural/urban interfaces and can impact sensitive populations such as children, asthmatics, and the elderly. In order to maximize the ability of land managers and farmers to utilize planned burning activities for ecological and crop productivity, while at the same time avoiding adverse air quality impacts, tools for predicting the impacts of burning are necessary to balance conflicting goals (Sandberg et al., 1999) and effectively manage smoke.

In many parts of the world fire is seasonally a large component of the atmospheric chemistry and atmospheric burden of pollutants, contributing significantly to ozone formation, $PM_{2.5}$ emission and formation, and emissions of other trace gases into the atmosphere. Therefore, global air quality prediction systems have begun incorporating fire emissions. Examples include Goddard Earth Observing System global chemical transport model (GEOS-Chem; Bey et al., 2001), Fire Locating and Modeling of Burning Emissions (FLAMBE; Reid et al., 2001), and the Navy Aerosol Analysis and Prediction System (NAAPS, http://www.nrlmry.navy.mil/aerosol/), which are run in real-time or near real-time.

Unlike these global systems, most regional air quality prediction systems do not yet routinely include fire emission estimates in their emission inventories and output products. However, four air quality dispersion systems not only include fire emission data but also provide smoke predictions from fire. These systems all have well-defined user bases and produce real-time predictions available via the Web, by integrating with burn information systems (both land-based and satellite-based). The USDA Forest Service's (USFS) BlueSky system serves the smoke management community and operates regionally across the United States, using both prescribed and wildfire burn information. The U.S. National Oceanic and Atmospheric Administration (NOAA) smoke prediction system is designed to support the air quality community needs and operates nationally using satellite fire detections. Washington State University's ClearSky prediction system focuses on agricultural burning in the U.S. Pacific Northwest and contains user input burn information. The Australian Bureau of Meteorology smoke prediction system is operational for regional domains across Australia covering both wildfires and prescribed burning.

Smoke forecasts link together, either explicitly or implicitly, a number of steps including the amount of fuel available, the fuel consumed, the speciated emissions and when they are released, how high the plume rises, and the resulting smoke transport. Each of these steps can be modeled explicitly or simplified with bulk formula calculations that combine steps. Thus, smoke forecasts rely on a number of models and assumptions that make smoke predictions inherently uncertain. Before these regional real-time smoke prediction systems existed, the burden was on the land manager to gather the various inputs and run them with smoke prediction programs installed on their personal computer (PC), as discussed in Breyfogle and Ferguson (1996). Only single fires or a set of fires known by the user could be processed with these PC-based systems. The Department of Forestry in Florida, USA, developed the first online tool that integrates meteorological forecasts, GIS data, and smoke dispersion models to give a smoke prediction based on user-entered burn information (http://flame.fl-dof.com/wildfire/). With the advent of regional real-time smoke prediction systems that integrate the necessary data, despite the uncertainties associated with each smoke prediction, the systems profiled here are providing a point of interagency understanding between land managers and air regulators from which to negotiate the conflicting needs of ecological fire use while minimizing air quality health impacts.

This chapter compares and contrasts the four systems, their methodology, and user needs for each, in order to examine the common components and differences inherent in each approach to smoke forecasting. We first examine the components that make up a smoke prediction system in Section 22.2, before detailing the specifics of the four systems in Section 22.3. System evaluation issues are discussed in Section 22.4 and operational uses, both current and potential, are discussed in Section 22.5. Finally, we discuss the future of real-time smoke prediction systems in Section 22.6.

22.2. Components of a smoke prediction system

In order to model smoke from fire, a smoke prediction system links together a series of logical steps, as shown in the schematic in Fig. 22.1. Dispersion models require knowledge of fire emissions distributed over time, which in turn rely on knowledge of the amount of fuel consumed. This process begins with the primary inputs: fire activity data such as fire size and location, and atmospheric model data describing the full three-dimensional state of the atmosphere as it evolves over time. It ends with smoke concentrations, typically in terms of particulate matter (PM) with an aerodynamic diameter less than or equal to 2.5 μm ($PM_{2.5}$), estimates of plume extents, and trajectories showing where a neutrally buoyant parcel of air will travel over the course of the next several hours. Some real-time smoke prediction systems also include information about other trace gases and aerosols emitted from fires, such as carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), hydrocarbons (HC), oxides of nitrogen (NO_X), ammonia (NH_3), and particulate matter with aerodynamic diameter less than 10 μm (PM_{10}).

By linking together the latest information in fire tracking, meteorological forecasts, fuels, consumption/emissions, dispersion, and trajectories, smoke prediction systems integrate the current state of knowledge in all of these areas. Each modeling step is discussed in detail below.

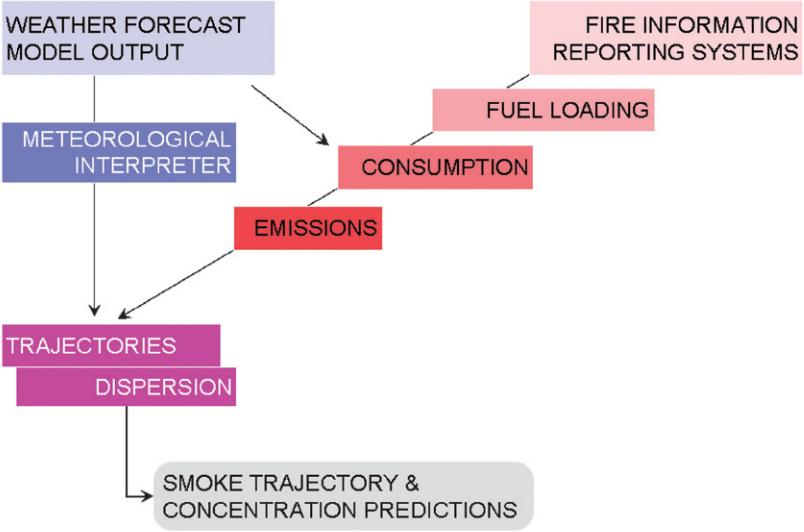


Figure 22.1. Modeling and data components of smoke prediction systems.

22.2.1. Meteorological data inputs

The availability and quality of the meteorological predictions are a key factor controlling the accuracy of the smoke predictions. Meteorological inputs are supplied by real-time weather prediction models such as the Pennsylvania State University/National Center for Atmospheric Research 5th generation Mesoscale Meteorological (MM5) model (Grell et al., 1994), the Weather Research and Forecasting (WRF) model (Skamarock et al., 2005), the North America Model (NAM, Janjic, 2003, formerly known as the Eta model, Mesinger et al., 1988), the Global Forecast System (GFS, Kalnay et al., 1990), or the Australian Limited Area Prediction System (LAPS; Puri et al., 1998). The accuracy of the meteorological forecasts, particularly the wind speed and direction and planetary boundary layer height, directly control the resulting accuracy of the smoke prediction.

22.2.2. Fire activity data inputs

To create a smoke prediction, fire information—minimally location and some measure of area burned—is needed. This can be obtained from ground-based reporting systems or remotely sensed from satellites. The information available varies widely, particularly from ground-based systems, which are usually driven by regulatory requirements. Some systems only record a wide range of potential dates for a permitted burn and not actual ignitions; some report only total fire size even for multi-day burns such as wildfires; some have significant (multi-day) lags before information becomes available. In each case care must be taken to appropriately use the recorded information. Consistency in the reported data (e.g., types of burns reported) is also problematic as databases maintained by regulatory agencies vary from region to region.

Detecting fires by satellite can provide a complete and relatively homogenous picture of where fires are currently occurring. A variety of satellite products are available, with perhaps the most popular platforms being the polar satellites (NASA's MODerate Resolution Imaging Spectroradiometer-MODIS, and NOAA-15/17/18) due to their higher spatial resolution (1 km). Depending on the product used, reports can be obtained within 15 min to 3 h of detection, and coverage can be continuous from geostationary satellites (e.g., the Geostational Operational Environmental Satellite (GOES)), or daily swathes from polar orbiting satellites (e.g., MODIS). Combined reports are also available. In all cases, however, satellite detections suffer from coverage issues, as clouds and thick smoke obscure fire detection. Polar orbiting satellites also have issues of variable swath timing for a given location, thus potentially missing (not detecting) short duration fires such as prescribed fires, agricultural burns and other small fires. However, the satellite sensor can detect fires as small as 0.5 ha under optimal conditions.

22.2.3. Fuel loadings

Quantification of the fuels that are burning is necessary in order to estimate emissions. Fuel-loading information can be provided as part of the fire activity data, obtained from regional maps of fuel load estimations, or set at some best estimate for a region or burn type. In the United States there are two national maps of fuel loadings, both on 1-km grids: the National Fire Danger Rating System (NFDRS; Cohen & Deeming, 1985) and the Fuel Characteristic Classification System (FCCS; McKenzie et al., 2007). In the future, mapped fuel loadings that extend beyond national borders will be necessary to provide consistent fuel-loading estimates for systems operating at an international and global scale.

22.2.4. Fire growth

To create a smoke prediction, fire growth must also be estimated over the future period of interest. In the case of prescribed fire and agricultural burns, this growth is known and can be utilized. For wildfires, growth must be calculated. Most real-time smoke prediction systems assume simple growth equations such as persistence (fire growth tomorrow = fire growth today).

22.2.5. Consumption and emissions

After determining the fire growth, fuel consumption and emissions can be modeled. Fuel consumption and emissions are a function of the efficiency of combustion, which is a function of the fire lighting technique, fuel moisture, and atmospheric conditions. Consumption models estimate the quantity of fuel consumed by a fire, utilizing meteorological and fuel moisture conditions. Emissions models then apply emission factors to the consumed material for various gases and aerosols, including CO, CO_2, CH_4, HC, NO_X, NH_3, $PM_{2.5}$, and PM_{10}. Consumption and emissions models are sometimes combined, such as in the commonly used Emissions Production Model (EPM)/CONSUME model (Sandberg & Peterson, 1984). Most consumption and emissions models (such as EPM/CONSUME) rely on emission factors based on empirical data measured from burns conducted under a variety of atmospheric conditions and fuel types (Andreae & Merlet, 2001; Battye & Battye, 2002). The Fire Emissions Production System (FEPS; Anderson et al., 2004) uses combustion efficiency to calculate fuel consumption and emissions, and efforts are underway to incorporate FEPS into real-time smoke prediction systems. For uniform fuels (such as wheat stubble and seed crop residue) fire emissions can be estimated from the fire spread rate and fuel loading.

22.2.6. Dispersion and trajectory models

Smoke transport can be simulated using either Lagrangian trajectory or dispersion models, or Eulerian air quality modeling systems. Trajectory models provide information on the location of the plume, while dispersion models also provide plume concentration values. Typically smoke prediction systems focus on Lagrangian particle or puff models, while air quality modeling systems that extend beyond fire smoke utilize more complex Eulerian chemistry models. Two U.S. air quality dispersion models currently used in real-time smoke predictions systems are the Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT; Draxler & Hess, 1997, 1998) and the CALifornia Lagrangian PUFF (CALPUFF) model (Scire et al., 2000).

HYSPLIT was developed and is maintained by NOAA's Air Resources Laboratory (ARL) and is designed to support a wide range of simulations related to the transport, dispersion, and deposition of pollutants, including ash from volcanic eruptions, smoke from wildfires, and emissions of anthropogenic pollutants. HYSPLIT can compute both trajectories and particulate concentration fields from a pollutant source. The HYSPLIT computation is composed of three components: particle transport by the mean wind, a turbulent transport component, and the computation of air concentration. Recent revisions to the model to support the smoke forecasting include a plume rise component and links with fire emission models. At a minimum, HYSPLIT requires three-dimensional fields of the vector wind components and temperature.

CALPUFF was developed by Sigma Research Corporation (now part of Earth Tech, Inc.) and is a U.S. Environmental Protection Agency (EPA) recommended guideline model for regulatory applications estimating air quality impacts (40 Code of Federal Regulations (CFR) 51 Appendix W). CALPUFF is a Gaussian puff dispersion model that simulates nonsteady point, volume, line, and area source emissions, and the resulting downwind concentrations by assuming that plume dispersion occurs in a Gaussian pattern. For buoyant area sources (such as fires), CALPUFF estimates plume rise, accounting for differences between the plume and ambient air temperatures and providing for mixing between the two as the plume advects downwind. Puffs are released at flame height, which is calculated from Cetegen et al. (1982) using the heat-released estimates from EPM. CALPUFF requires three-dimensional fields of the vector wind components and temperature, and two-dimensional fields describing atmospheric stability and mixing height.

Table 22.1 summarizes the source of fire activity, fuel-loading information, and the consumption, emission, meteorological, and air quality data/models used in each of the real-time smoke prediction systems.

22.3. Real-time smoke prediction systems

Several real-time smoke prediction systems are currently operational around the globe, providing predictions of smoke concentrations from fire to a clientele of land managers, farmers, and air quality regulators. Profiled below are four systems currently operational for regions of North America and Australia that provide forecasts to well-developed user communities.

22.3.1. BlueSky: Predicting smoke from prescribed and wildland fires regionally across the United States

The concept of the BlueSky smoke modeling framework was developed in the U.S. Pacific Northwest by a group of land managers, fire researchers, and air quality regulators seeking to link existing information about fire, fuels, meteorology, and air quality into a system that could aid in smoke management. BlueSky's original goal was to help burners understand where the smoke from a burn will go before it is ignited; however, BlueSky's use has expanded to include wildfire incident command teams and air quality regulators (O'Neill et al., 2005).

BlueSky is a modular framework of fire activity, fuels information, consumption, emissions, meteorological, and air quality modeling systems that produces daily predictions of $PM_{2.5}$ concentrations across the region. The USFS Atmosphere and Fire Interaction Research and Engineering (AirFIRE) Team (http://www.fs.fed.us/bluesky) leads the development efforts of the system. By defining standard interfaces, BlueSky is able to implement a variety of model choices at each modeling

Table 22.1. Source of fire activity, fuel loading, and the consumption, emission, meteorological and air quality data/models used in each of the real-time smoke prediction systems

	Fire activity	Fuel loading	Consumption model	Emissions model	Meteorological model	Dispersion model
BlueSky	Ground-based, satellite	FCCS	CONSUME	EPM	MM5/WRF	CALPUFF, HYSPLIT
ClearSky	Ground-based	kg/ha[a]	100%	g/kg[a]	MM5/WRF	CALPUFF
NOAA	Satellite	NFDRS	CONSUME	EPM	NAM-WRF/GFS	HYSPLIT
Australia	Ground-based, satellite	None	None	Single fixed emission rate	Australian meso-LAPS	HYSPLIT

[a] Estimates provided for wheat stubble and Kentucky bluegrass residue burning.

step (the most common choices are listed in Table 22.1). Additionally, since the framework can be started and stopped at any interface, BlueSky can be used to process emissions for other smoke prediction efforts, such as inputs to Eulerian air quality models or hind-casts of smoke impact episodes.

Currently, daily BlueSky predictions of surface $PM_{2.5}$ concentrations are available across the U.S. through a collection of regional modeling efforts run by the USFS Fire Consortia for the Advanced Modeling of Meteorology and Smoke (FCAMMS; http://www.fs.fed.us/fcamms; Fig. 22.2a). Additionally, BlueSky-processed wildfire emissions are used in other smoke prediction systems including the ClearSky and NOAA systems discussed below. In the U.S. Pacific Northwest, wildfire emissions are processed through BlueSky into a format for input into the Community Multi-scale Air Quality (CMAQ; Byun & Schere, 2006) modeling system as described in Pouliot et al. (2005) and used in the AIRPACT-3 (Vaughan et al., 2004, http://www.airpact-3.wsu.edu) air quality forecast system operational for the northwestern United States. This was the first inclusion of daily fire information in a real-time Eulerian air quality modeling system to predict downwind chemical concentrations from fires.

BlueSky has been developed to be flexible in how it obtains and utilizes fire activity data, partially because of the wide variety of reporting systems implemented regionally in the U.S. At a minimum, BlueSky requires fire location and daily fire growth, which can be problematic for wildfires in which typically only fire size and initial ignition point are reported. If additional fire activity data, such as fuel loadings, fuel moisture, and fire type, are included in the input, this information is carried through the framework and used preferentially. If this information is not available, default values or models are used.

For regional forecasts by the FCAMMS, BlueSky is connected to a variety of ground-based fire-reporting systems and automatically downloads data from these systems. BlueSky uses a variety of generic download methods, including a Web form interface to allow outside users to enter information on their fire, as well as a simple Web or ftp download. Nationally, BlueSky is connected to the U.S. national wildfire and wildland fire use reporting system, via the Incident Command System (ICS)-209 reports. The daily ICS-209 reports contain information, such as current area burned and ignition location for wildfires typically greater than 100 acres in size. Regionally, for the U.S. Pacific Northwest,

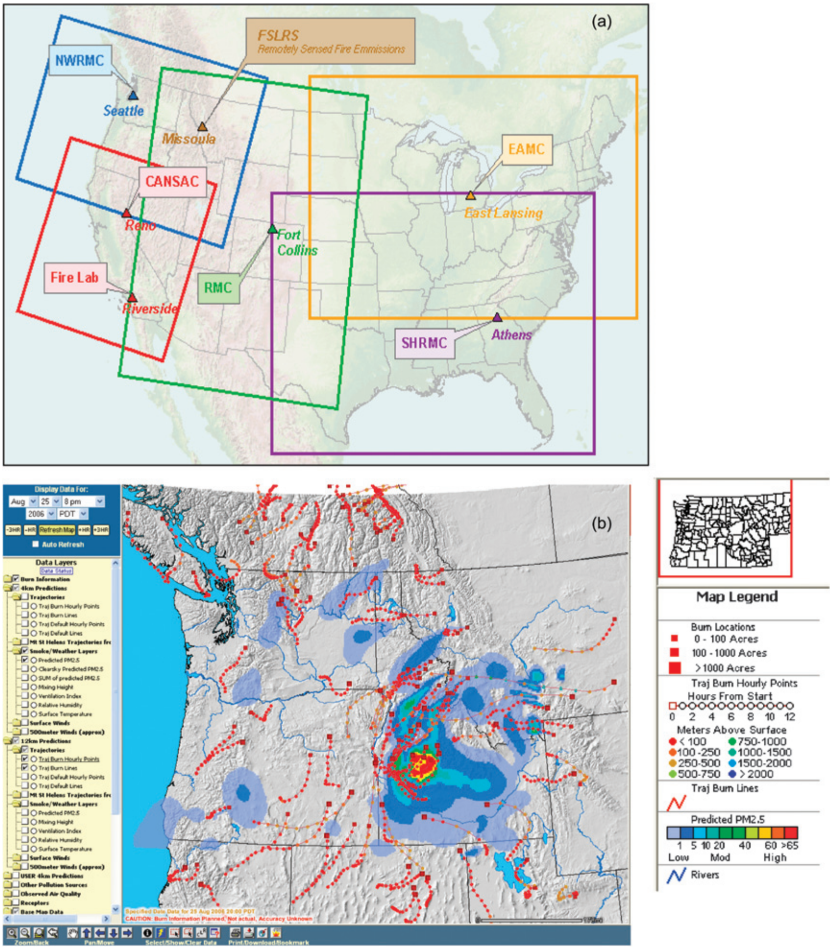


Figure 22.2. Location of regional BlueSky predictions across the U.S. implemented by the USDA Forest Service Fire Consortia for the Advanced Modeling of Meteorology and Smoke (FCAMMS; http://www.fs.fed.us/fcamms) (a). BlueSkyRAINS output for August 25, 2006, at 8 P.M. $PM_{2.5}$ concentrations (colored contours in units of $\mu g/m^3$) and trajectories (initiated at red squares) predicted from wildfires across the northwestern U.S. and western Canada are overlaid on gray-shaded topography. Trajectory dots are color-coded with height (see map legend, b). Acronyms: Northwest Regional Modeling Consortium (NWRMC), California and Nevada Smoke and Air Committee (CANSAC), Rocky Mountain Consortium (RMC), Southern High Resolution Modeling Consortium (SHRMC), Eastern Area Modeling Consortium (EAMC). Forest Service Lab-Remote Sensing (FSLRS).

BlueSky is connected to many ground-based prescribed fire-reporting systems including:

- The Fuel Analysis, Smoke Tracking, and Report Access Computer System (FASTRACS; http://www.fs.fed.us/r6/fire/fastracs), which includes federal prescribed fire data in the states of Oregon and Washington.
- The Montana/Idaho airshed group prescribed burn reporting system, which includes private, state, and federal prescribed fire data in the states of Montana and Idaho.
- The Washington State Department of Natural Resources system, which includes private, state, and federal prescribed fire data in Washington State.
- The Oregon Department of Forestry burn reporting system, which includes private and state prescribed fire data in Oregon State.
- The British Columbia wildfire reporting system.
- The ClearSky agricultural burn prediction system, which includes private and tribal agricultural fire data in the states of Washington and Idaho.

Also, BlueSky is now connected to a system that reconciles these ground reports with satellite fire detects from the NOAA Hazard Mapping System. This system will become the default for FCAMMS BlueSky predictions across the United States in summer 2008.

With all prescribed burning operations there is a difference between what is planned for a particular day and what is actually accomplished. BlueSky also obtains burn accomplishment reports from the above systems where available to initialize each forecast with carry-over smoke from the previous day's burn.

Meteorological data, used to drive the emission estimates and dispersion and trajectory models can be obtained from several sources, including the MM5 and/or the WRF mesoscale meteorological models. The meteorology defines the domain of the BlueSky simulation, another feature that allows BlueSky's quick and easy adaptation to domains nationally and internationally. BlueSky is typically run on 4-km and 12-km grids; however 1-km and 36-km gridded domains have also been applied over North Carolina and the western United States, respectively (http://www.fs.fed.us/bluesky).

Many different models are available for each calculation step in BlueSky; here we describe only the most common configuration. If fuel-loading information is not provided by the user or the burn reporting system, then the U.S. 1-km FCCS mapping is used by default. Consumption and emissions are calculated by the EPM model, which is integrated with the CONSUME model. For prescribed fires, EPM provides an emission profile allocating emissions over time, while for wildfires, the diurnal emissions profile developed by the Western Regional Air Partnership (WRAP; http://www.wrapair.org) is applied. $PM_{2.5}$ concentrations are estimated using the buoyant area source input method of CALPUFF. The HYSPLIT model is used to calculate trajectories from each fire. Currently, trajectories are released at a height of 10 m and travel for 12 h so that a land manager can view not only where smoke from a particular burn may travel through the day but where the smoke goes into the evening when it can become trapped in mountain valleys. Efforts are underway to incorporate plume rise estimates into the trajectory release height.

Graphics of BlueSky output are produced in two forms: (1) static and animated images and (2) the RAINS (Rapid Access Information System), Geographical Information System (GIS)-based Web interface, developed by the EPA in the U.S. Pacific Northwest. Figure 22.2b shows an example of the BlueSkyRAINS (http://www.fcamms.org) display of $PM_{2.5}$ concentrations and trajectories from wildfires across the northwestern United States and western Canada. RAINS allows the user to customize the display by zooming in and out—selecting various data layers, such as smoke concentrations and trajectories, meteorological forecasts, sensitive receptors, roads and terrain—and obtaining quantitative results from a variety of database queries. Features of RAINS include the ability to query the underlying data to obtain fuel-loading information and total emissions of $PM_{2.5}$, CO_2, CO, CH_4, NO_X, HC, SO_2, and PM_{10}, and access data from air quality monitoring networks.

22.3.2. ClearSky: Predicting smoke from agricultural fires in the northwestern United States

In the arid intermountain region of the northwestern United States, which includes the eastern part of Washington State, parts of the Idaho Panhandle, and parts of eastern Oregon, smoke from agricultural burning, a typical practice in this region, has become a subject of litigation, legislation, and governmental and scientific interest. In January 2001, the Idaho Division of Environmental Quality proposed creation of a smoke modeling tool for decision support in the Idaho smoke management program administered by Idaho's Department of Agriculture. This led to the development of Washington State University's ClearSky smoke prediction system (http://www.clearsky.wsu.edu).

Agricultural burning in this area is primarily of two kinds: wheat stubble and residue after harvest of Kentucky bluegrass (KBG), a

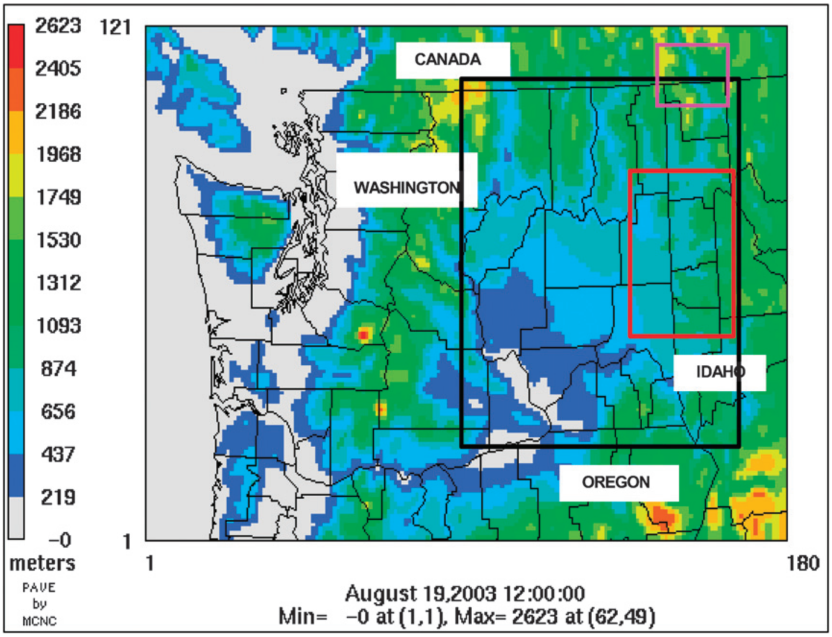


Figure 22.3. ClearSky domain elevations. The red rectangle indicates the original application for the Rathdrum Prairie and Coeur d'Alene tribal reservation. The black rectangle indicates the expansion to Eastern Washington and the Nez Perce Tribal reservation in Idaho. The pink rectangle indicated the application for boundary county, Idaho.

profitable seed crop. ClearSky was initially formulated for treatment of smoke for burning on the KBG fields of the Rathdrum Prairie near Coeur d'Alene (CDA), Idaho, and also for burning on the nearby Coeur d'Alene tribal reservation (Fig. 22.3, red rectangle). The ClearSky system became operational in the summer of 2001 for the Rathdrum Prairie and CDA areas, and was significantly expanded in 2002 to include eastern Washington and the Nez Perce Tribal (NPT) reservation (Fig. 22.3, black rectangle).

Operationally, ClearSky uses the 4-km real-time MM5 numerical meteorological domain prediction from the University of Washington (Mass et al., 2003), and emission scenarios defined by users, to drive a CALPUFF simulation producing hourly surface level $PM_{2.5}$ concentrations. Fundamental to the concept of ClearSky is the user generating a hypothetical burn scenario for their jurisdiction and reviewing the ClearSky results for that burn scenario before making decisions to ignite a burn. Field burning scenarios are defined via a Web-application the day before, and the simulation runs overnight after the meteorological forecast becomes available. Typically, about 10 scenario forecasts are run nightly, including a set of default scenarios. Comprehensive databases of fields from which the users create scenarios have been created specific to the Coeur d'Alene Tribe, Rathdrum Prairie, Nez Perce Tribe, and Washington State Department of Ecology operational regions. Animations of gif images are produced for viewing the $PM_{2.5}$ concentration fields on the Web and are used by the local state and tribal agencies in their burn decision-making process.

In converting acreage and crop type into emissions parameters, information such as areal burn rates (ha/h), fuel loadings (kg/ha), and emission factors (g/kg) must be specified. Areal burn rates and fuel loadings are estimated based on agency expertise and are included in the database of agricultural fields. Emissions factors are based on values from wheat stubble and KBG from studies conducted by Air Sciences, Inc. (2003, 2004).

The initial ClearSky treatment of emissions assumed that the plume from a field of burning stubble should be handled through CALPUFF's buoyant area-emissions capability. Observation of field burning suggested that addition of a line source might better capture the intense buoyancy associated with the flaming front in a field fire. Particulate production is most strongly associated with combustion stages that are not flaming, primarily post-flaming smoldering (Ward, 2001). Field observations show that the buoyancy from the flame front generates horizontal flows of replacement air, which entrain much of the smoke produced by nearby non-flaming combustion that carries the smoke into the flame front. Therefore, a buoyant line source is used to simulate the flaming front, in addition to an area source.

Another research effort to improve the ClearSky predictions and provide a measure of uncertainty explored using an ensemble of 17, 12-km MM5 meteorological simulations to generate an ensemble of CALPUFF $PM_{2.5}$ predictions, thereby providing probabilistic guidance (Heitkamp, 2006). ClearSky ensembles were analyzed for 2 days with heavy field burning in 2004, using accomplished burn data (Jain et al., 2007). Ensemble average hourly $PM_{2.5}$ results were compared with hourly monitoring results to calculate normalized mean error in $PM_{2.5}$ for each day. The 12-km ensemble system average results were encouraging, showing slightly better error statistics than the original 4-km ClearSky system.

22.3.3. The NOAA-HYSPLIT smoke forecast system: Predicting smoke from satellite sensed fires across North America

NOAA's interest in fires and smoke started in the spring of 1998 during the massive transport of smoke from fires in Central America across

Texas, the southeast United States and as far north as the Mid-Atlantic States. In response, an operational fire and smoke program at NOAA's National Environmental Satellite and Data Information Service (NESDIS) was developed primarily to support National Weather Service (NWS) needs in that region. As part of that program the Hazard Mapping System (HMS) was developed in 2001 (Ruminski et al., 2006) as an interactive tool to identify fires and smoke produced over North America in an operational environment. The NOAA-HYSPLIT "Interim Smoke Forecast Tool" was then implemented until the fire emissions could be implemented in the operational air quality modeling (Otte et al., 2005).

The HMS fire detection system uses two geostationary and five polar orbiting environmental satellites with automated fire detection algorithms employed for each sensor. The polar satellites (NASA's MODIS and NOAA-15/17/18) are the preferred platforms for determining fire size due to their higher spatial resolution (1 km). Each algorithm utilizes multispectral imagery and applies a form of temperature threshold to evaluate each hotspot. The HMS analysis domain includes all of North America but is adjusted seasonally to include each specific region's prime burning activity season (i.e., Central America in spring, Alaska in summer).

Human analysts use visual satellite imagery and apply quality control procedures for the automated fire detections to eliminate hot spots that are deemed to be false and to add hot spots that the algorithms have not detected. The addition and deletion of fire locations are based on analyst experience in satellite image interpretation, consistency of a fire signal across image times and platforms, and confirmation via the presence of smoke emissions. (These data are available daily at: http://www.firedetect.noaa.gov.)

The NOAA real-time smoke prediction system (http://www.arl.noaa.gov/smoke/forecast.html) uses the HYSPLIT dispersion model coupled with the NAM-WRF meteorological data, which is run on a 12-km grid at intervals of 1-hr over the continental United States; and the 3-h 1-degree grid-spacing GFS data fields for any fire locations that may be outside of the NAM domain. Therefore, the smoke prediction system can include fires in Alaska, Canada, and south through Central America, approximately 7–75 degrees north latitude. Fires identified as producing smoke in the satellite imagery by the HMS analysts are utilized. These fires are a subset of all fire hot spots. The number of input points representing a fire is considered to be proportional to an approximation of the areal extent of the fire. Dispersion calculations are run once a day using the 0600 UTC forecast cycle. Hourly average output maps of $PM_{2.5}$ concentrations are produced using the HMS fire locations for the previous day. Because of the concern over the effects of fine particulates, the model simulation is focused on $PM_{2.5}$ concentrations, although any species available in the emission inventory could be modeled. The dispersion simulation consists of a 24-h analysis simulation run for the previous day, and a 48-h forecast simulation, which assumes that yesterday's fires will continue to burn today and tomorrow unless fire duration information is available for a particular fire. The smoke particle positions at the end of each analysis period are used to initialize the next day's analysis simulation.

$PM_{2.5}$ emissions and heat released are estimated from the emissions processing portion of the BlueSky system based on fire size and location. The system consists of the EPM model integrated with the CONSUME model and the NFDRS fuel loadings. The fire area is computed from the sum of the number of fire locations provided by the HMS analysis within an emission aggregation grid currently set to a 20-km resolution. In the smoke prediction computation, particles are released at the final plume rise height from the center of each emission grid cell that contains one or more fire locations. The heat release rate from EPM/CONSUME, in conjunction with the forecast meteorology, is used to compute a final plume rise (Briggs, 1969).

Two $PM_{2.5}$ concentration grids are defined for each simulation, each having a grid spacing of 15 km. One grid creates hourly averaged $PM_{2.5}$ concentrations from the ground to 5 km (Fig. 22.4) for comparison with satellite smoke plume observations. The second grid defines the layer in the lowest 100 m as hourly average $PM_{2.5}$ concentrations for air quality applications.

The official NWS hourly graphical output for each forecast hour over the continental United States is posted daily as part of the Air Quality Forecast Guidance from the NWS National Digital Guidance Database (http://www.weather.gov/aq). An archive of data for 30 days as well as the current forecast maps for various geographic regions or the national domain are available from NOAA's Air Resources Laboratory's web page (http://www.arl.noaa.gov/smoke/forecast.html).

Although the NOAA-HYSPLIT smoke prediction system features the incorporation of real-time satellite fire detection data, these data are a source of uncertainty. The number of fires undetected by the automated algorithms and added by analysts can represent over 50% the annual total. Some of this is due to the navigational discrepancies between the satellites and variation even from image to image for the same satellite platform. Thus, a single fire may be represented by multiple automated hot spots clustered around the actual fire location. Another major issue is predicting which fires will be continuous through the forecast period.

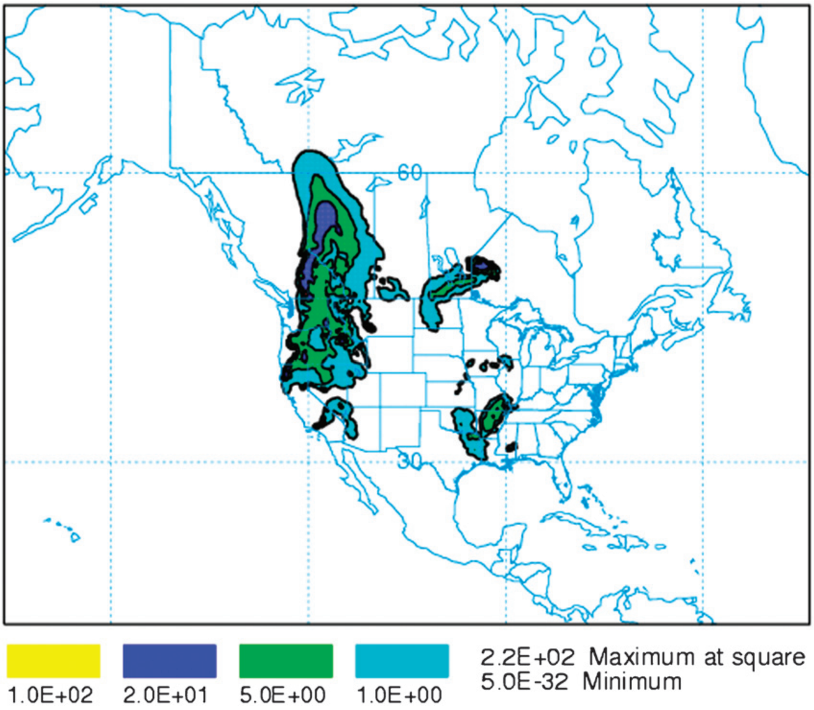


Figure 22.4. One-hour average (6 am–7 am 9/9/2006) 0–5000 m column integrated $PM_{2.5}$ concentration calculated by the NOAA-HYSPLIT smoke prediction system at the end of the 24-hour analysis period used for the initialization of the 48-hour forecast.

Some fires, such as large wildfires, are both easily detected and likely to continue to burn. However, this is not the case for most of the agricultural and prescribed burns and many of the small wildfires. The fire area is currently determined by the number of detections in a grid cell—this can also be problematic for the smaller fires.

The HMS smoke plume analysis is used to evaluate the NOAA-HYSPLIT smoke prediction. As part of the HMS, areas of smoke are outlined by an analyst using animated visible channel imagery. Visible band imagery is used to detect the HMS smoke plumes, but clouds can hinder detection during the day, and detection is not possible at night. In November 2006, a quantitative estimate of the smoke concentration associated with the HMS plume analysis was implemented. The estimation is based on output from the GOES Aerosol and Smoke Product (GASP; Knapp, 2002) and visual inspection of the plume. While

GASP utilizes reduced 4-km visible band imagery, the analyst views the full 1-km resolution available from GOES. Three categories of smoke concentration are specified by the analyst: 5 (light), 16 (medium), and 27 (thick) $\mu g/m^3$. This single value is the midpoint of a range of values that are being represented: 0.1–10.5 $\mu g/m^3$ (light), 10.5–21.5 $\mu g/m^3$ (medium), and greater than 21.5 $\mu g/m^3$ (thick).

22.3.4. Predicting smoke from wildfires in Australia

The Australian Smoke Management System (Wain & Mills, 2006) was developed to assist land managers in planning prescribed burns while mitigating impacts of smoke from these fires. The climatological window for prescribed burning in southern Australia occurs in the Australian spring and autumn, avoiding summer drought and winter rains. Unfortunately, optimum conditions for prescribed burning coincide with typically anticyclonic weather patterns, providing less then ideal dispersion conditions. Dispersion forecasts are also issued based on hot spots identified from MODIS satellite imagery to provide information on smoke from wildfires.

Components of the system are the meteorological fields from the Numerical Weather Prediction (NWP) systems operated by the Australian Bureau of Meteorology (the Bureau) and transport and dispersion calculations from the HYSPLIT model. Specifically, the smoke prediction system relies on several higher resolution domains (0.05 degree) over the populated areas of the country as shown in Fig. 22.5. Concentration grids are output at four vertical levels: 10, 150, 500, and 1500 m. For the initial system implementation a source concentration of 1 arbitrary unit has been specified, with the forecast concentrations being relative to this value. This was done because of large uncertainties in the fuel-loading information and lack of an emissions model. The outermost contour interval for the concentration forecasts was selected to coincide with the edges of the visible smoke plume based on field studies where both aircraft and ground observations of the smoke plumes from prescribed burns were made. The plume rise was initially set arbitrarily at 1500 m, the approximate height of the typical subsidence inversion during ideal autumn prescribed burning conditions. It has been found that using the depth of the mixed layer, as diagnosed by the NWP model and input to the dispersion model, to specify the plume height greatly improves the predictions (Wain, 2006). This assumes that the fire is a low-intensity burn as typified by many prescribed burns, rather than a high-intensity burn where the plume may penetrate the inversion (as in large wildfires).

Product delivery has been designed in close collaboration with land managers in order to complement their decision-making processes.

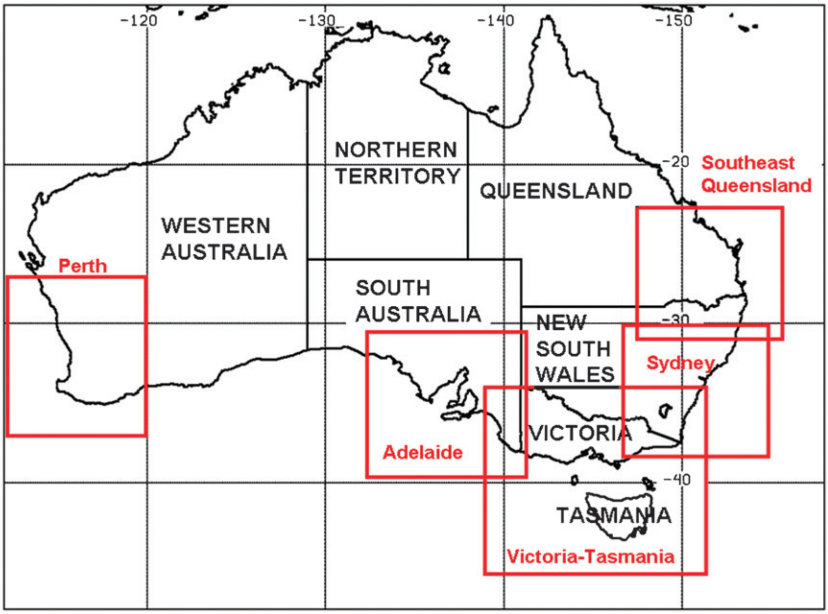


Figure 22.5. The Australian mesoscale domain. Smoke predictions are issued for the higher resolution 0.05° grid-spacing regions in red. State boundaries are in bold black, state names in bold black capitals, and the locally used descriptors for the high-resolution model domains are labeled in red.

The guidance is delivered via a password-protected Web site, with individual pages for each state. Within each state the land management agencies have nominated a number of locations representative of their major forestry operations for the coming season, which forms a set of fixed source points used throughout each prescribed burning season. The number of these fixed source points per state ranges from 6 (Tasmania) to 16 (Northern Territory). Dispersion forecasts are prepared based on each of these potential fire locations, with ignition times each day spanning the times during which fires would normally be lit. These times have been chosen by each state to suit their operational practices, with the earliest ignition time being 1000 local time and the latest 1600 local time, and with emission intervals of either 2 or 3 h.

Within each state, the dispersion prediction shows only three or four source points on a single display panel, to reduce the possibility of overlapping plumes making interpretation difficult—the guidance is intended to show where smoke from a single potential fire may impact, not the combined forecast concentrations from a number of actual fires.

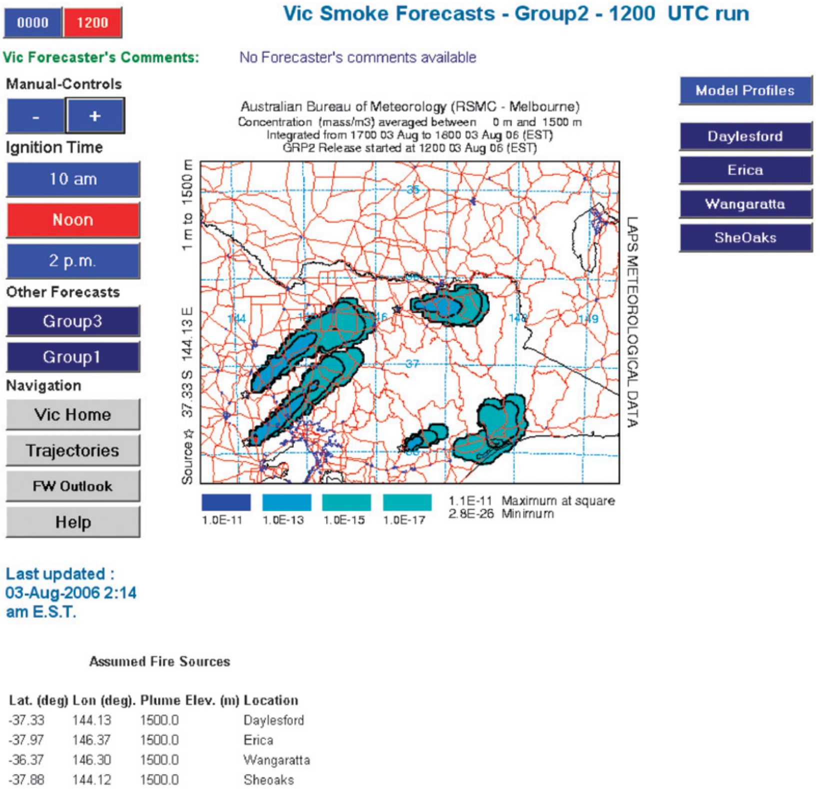
A separate set of dispersion forecasts are issued for the country, based on hot spots identified in MODIS satellite imagery by Geosciences Australia using their Sentinel system (http://sentinel2.ga.gov.au/acres/sentinel/index.shtml). These are used to assist community understanding of the source of smoke from wildfires.

In Australia, the smoke prediction system is run twice a day based on the 0000 UTC and 1200 UTC meteorology. The 0000 UTC run completes early in the afternoon to provide guidance for broad decision making for the next day's burning program. Then, the 1200 UTC run executes overnight, and results are available in the early morning for finalizing whether to ignite a burn at sites provisionally selected the previous afternoon. The system also allows the land management agency to interactively change a standard burn location to one of particular interest before the 1200 UTC dispersion predictions are initiated.

A typical page from the guidance products is shown for Victoria in Fig. 22.6. The dispersion panel shows the average concentration between the surface and 1500 m from 1700 to 1800 EST, following a noon ignition. Roads, rivers, and townships are shown to assist planning. The presentation can be animated or stepped manually ("Manual Controls"), and the user can select an earlier or a later forecast base time (top left), an ignition time (upper left), or other station groups (middle left). There is a range of supplementary information that can be accessed through this page to assist the decision maker. In the lower left (the gray buttons), the user can select "Trajectories" (Fig. 22.6). Under this option a larger number of forward trajectories, representing the mid-line of the dispersion plumes, can be displayed, or alternatively, backward trajectories from "high impact" sites can be displayed. This latter form of guidance may indicate areas where fires should NOT be ignited if these sensitive locations are not to be impacted by smoke. In the upper portion of the panel there is provision for a forecaster to add interpretive comments to the guidance, and this facility is usually invoked only if a wind shift is mistimed by the model. This ensures consistency between these products and other fire weather meteorological forecasts. In the upper right of the panel forecast vertical wind, temperature, and humidity profiles at each of the source locations can be selected, and these include the predicted height of the mixed layer and the ventilation index at 3-h intervals.

22.4. Evaluation of real-time smoke prediction systems

Evaluation of smoke prediction systems is a complex task, and methodologies and techniques are continuing to evolve. Analysis of



Vic Forecaster's Comments: No Forecaster's comments available

Last updated : 03-Aug-2006 2:14 am E.S.T.

Assumed Fire Sources

Lat. (deg)	Lon (deg).	Plume Elev. (m)	Location
-37.33	144.13	1500.0	Daylesford
-37.97	146.37	1500.0	Erica
-36.37	146.30	1500.0	Wangaratta
-37.88	144.12	1500.0	Sheoaks

Figure 22.6. Predicted smoke concentrations (relative to a unit emission rate) averaged between the surface and 1500 m for August 3, 2006, from 1700 to 1800 EST for the Victoria, Australia, domain.

surface smoke concentrations are a primary concern because pollutants at the surface impact human and ecosystem health. However, limited ground-based measurements make it difficult to thoroughly evaluate model output, and model-to-point comparisons are complicated in complex terrain and confounded by the presence of other pollution sources. Satellite measures provide greater coverage, but are inherently limited to integrated measures of the entire atmospheric column. Additionally, apportioning the sources of error to the component models (fire activity, fuel loading, consumption, emissions, plume rise, dispersion, and transport) requires multiple case studies. This section details some of the techniques and results from a variety of evaluation efforts that have been performed.

Satellite imagery has proved very useful in monitoring smoke from the larger prescribed burns and wildfires, as long as the atmosphere is clear and the underlying surface and the smoke plume have different radiative properties. The best results using satellites are frequently obtained when the smoke plume is transported over the ocean, although there is still considerable uncertainty between the minimum concentration that a ground-based observer can discern and the smoke plume as seen in the imagery. A number of case studies of smoke dispersion from prescribed and wildfires are presented in Wain and Mills (2006).

Typically, two types of satellite data can be used in evaluation: Aerosol Optical Depth (AOD) measurements that represent a quantitative measure of integrated aerosol loading over the entire air column, and smoke plume extents. Because they integrate the entire air column, AOD observations require assumptions to allow allocation to specific heights in the atmosphere or require a vertically integrated result from the smoke prediction system for comparison, and this has limited its utility to date.

The NOAA-HYSPLIT real-time smoke prediction system uses the HMS smoke plume extents for evaluation. Figure 22.7 shows NOAA-HYSPLIT output alongside the HMS satellite smoke graphic and illustrates the basic evaluation metric—the "Figure of Merit in Space" (FMS), a fraction representing the ratio of the intersection to the union of

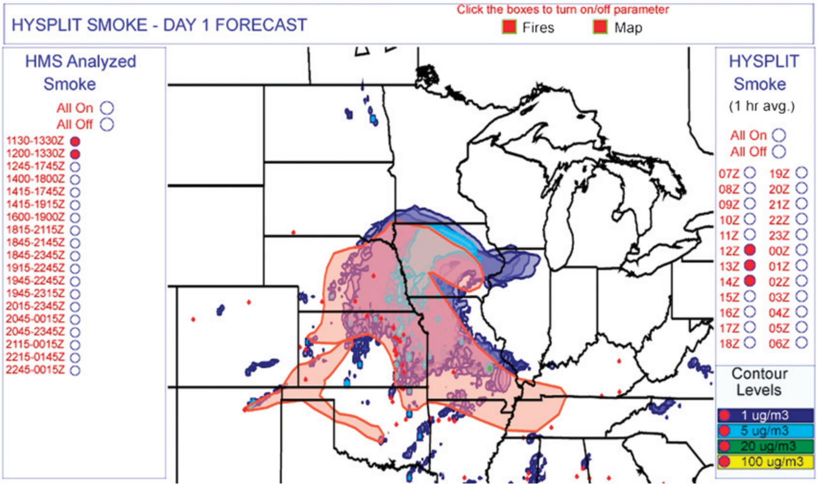


Figure 22.7. The 24-hour prediction for April 13, 2006, by the NOAA-HYSPLIT smoke prediction system available through the online archive, showing the model predictions at various concentration levels (blue and cyan) overlayed with the HMS observed smoke plume (red).

the analyzed and calculated smoke plume areas (higher is better). Because of uncertainties in fire detections and the possibility that some of the detected smoke is not due to the fire locations represented in the model, only smoke plumes with a non-zero overlap are included in the statistics. Furthermore, the FMS is computed for several concentration values (1, 5, 20, and 100 $\mu g/m^3$) because of uncertainties in the emissions and the threshold concentrations representing the visible edge of the HMS-analyzed smoke plume. Because it is not possible to assign a fixed threshold concentration to the HMS plume, the best verification contour may vary from day to day. Typical FMS values range from 10% to 20% for the 1 and 5 $\mu g/m^3$ contours. For instance, the FMS of the calculation shown in Fig. 22.7 is 15% when averaging all plumes with equal weights and 30% if the FMS is computed using an area weighting. A limitation of the FMS approach is that the statistic tends to show poorer performance than what might be suggested by a qualitative examination of the graphical smoke plume products. This is due to the fact that all nonoverlap plume regions result in an FMS of zero. Even for cases where there is complete overlap, if the measured or calculated plume is much larger than the other, the FMS will be reduced in magnitude. The NOAA-HYSPLIT real-time smoke prediction system regularly calculates both daily and 30-day running averages for real-time evaluation, allowing forecasters to judge the applicability of the current forecast based upon how well the fire locations and model predicted smoke compared with the actual smoke detection. Objective automated evaluation procedures are under investigation that use predicted grid point concentrations compared with satellite-derived aerosol optical depth values.

While satellite data can provide insight into overall performance, ground-based observations are also needed for predictive skill evaluation. In-situ monitoring networks of PM and trace gases can provide useful long-term evaluation data and are being used in several evaluation studies for the BlueSky, ClearSky, and Australian systems. Although such studies provide insight into overall predictive skill, they have several issues. Air Quality monitors are typically located at population centers, whereas agricultural and prescribed burning may only occur when concerned agency personnel judge that the approved burning will not significantly elevate $PM_{2.5}$ in those population centers (i.e., at the monitors). Thus, successful use of real-time smoke prediction systems should result in PM monitors showing no significant elevations in concentrations attributable to burning. Additionally, because these monitors are typically spaced hundreds of kilometers apart, many fires do not impact a monitor, and even when they do, the accuracy of the shape of the predicted plume cannot be judged. Thus, dedicated field campaigns are needed to obtain sufficient data downwind of active fires to characterize and evaluate system performance. Hess et al. (2006) discuss the use of in-situ monitors for evaluation of predictions from Australian wildfires.

Recent work (Liu et al., 2006) has shown that integration of basic fire behavior is necessary to simulate the larger wildfires. Many large wildfires are not a single convective column, but rather are multiple fire cores that are grouped together into a wildfire complex. Emissions from single convective column fires (single core) are released higher in the atmosphere relative to similar size fires that exhibit multiple convective columns (multiple core). Evaluation of the Rex Creek wildfire that occurred in 2001 in Washington State showed that simulating the wildfire as multiple smaller cores dramatically improved the results when comparing BlueSky model predictions with observations (Fig. 22.8). This fire behavior had

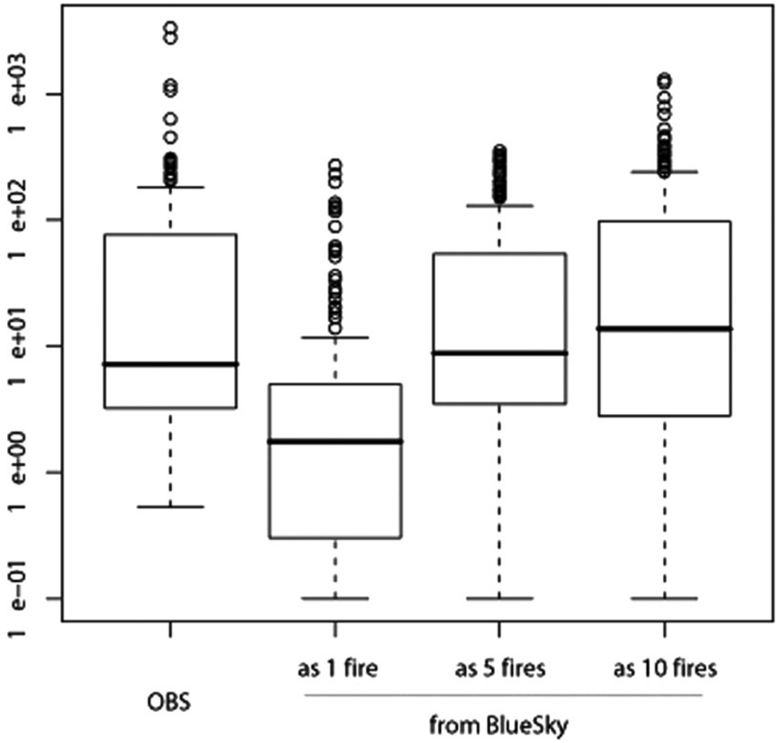


Figure 22.8. $PM_{2.5}$ concentrations near Twisp, Washington, for the Rex Creek fire for the period of August 19–26, 2001. Box-whisker plots show observed concentrations (OBS) and BlueSky concentrations for the one-fire, five-fire, and ten-fire cases. Values below 0.1 are set to 0.1 for plotting purposes.

greater impact on improving the prediction than various fuel models and consumption/emission algorithms (Larkin et al., 2008) and can be included in the forecasts without significant operational performance impact.

Evaluation of plume rise in ClearSky was undertaken in 2004, when plume rise measurements were made for four wheat stubble burns in Washington and five Kentucky bluegrass residue burns in Idaho (Heitkamp, 2006). Final plume height was measured by aircraft altimeter. ClearSky simulations were conducted for the nine field burns using plume rise parameterizations from Jain et al. (2007), based upon review of field burning studies conducted collaboratively by Air Sciences, Inc. (ASI), the USFS Missoula Fire Sciences Laboratory and Washington State University (Air Sciences, Inc., 2003, 2004). Figure 22.9 shows how for seven of the nine experiments, the ClearSky plume height results compared well to the observed plume heights.

22.5. Operational applications of a real-time smoke prediction system

Real-time smoke predictions have only become available in the last several years. While these systems were developed to address specific needs in forestry and agricultural burning, it is becoming clear that they possess utility far beyond their original purposes.

22.5.1. Prescribed fire and agricultural burning

Perhaps the clearest utility of real-time smoke predictions is in the decision process surrounding whether to ignite prescribed and agricultural fires. The goal is to provide the burner with information as to whether smoke from their fire, if ignited, will have impacts on sensitive receptors downwind or yield excessive concentrations. Past history has shown that these types of fires can have significant smoke impacts resulting in negative effects on health, public relations, and the acceptance of burning as a land management tool. The hope is that real-time smoke predictions can reduce such impacts and mitigate their negative consequences.

The Dutchler prescribed burn, which occurred approximately 20 miles (32 km) northwest of Salmon, Idaho, in September 2004, is an example of where a smoke prediction system could have been used to help mitigate smoke impacts. The plan was to burn over a period of 2 days, with 1000 acres burned on day one, and another 1200 acres on day two. However, smoke accumulated overnight in Salmon (population 3100), resulting in

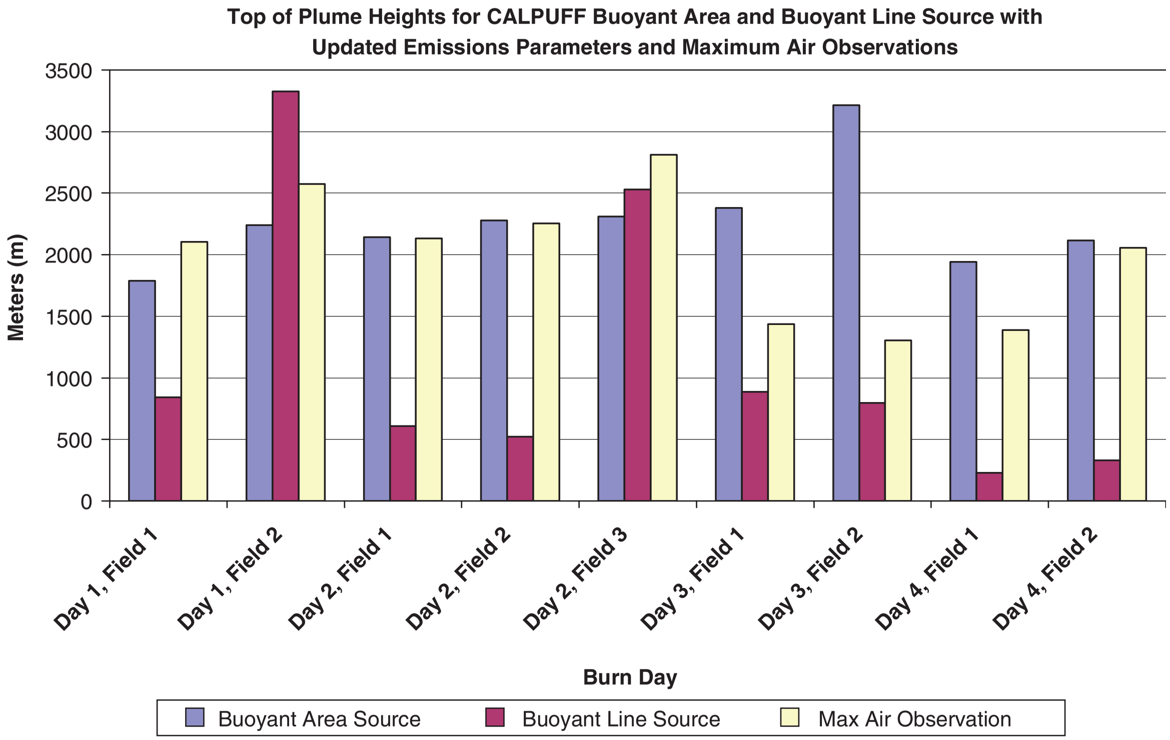


Figure 22.9. ClearSky plume rise results as calculated by CALPUFF, using updated plume rise parameters, and aircraft observed plume heights.

health complaints and multiple calls to city and county officials, prompting the mayor and county commissioner to contact land managers in charge of the burn. As a result, the second day's burn was cancelled, and considerable effort was necessary to repair relations with local officials and the public. Examination of BlueSky results, and in particular the trajectories from the burn and the ventilation index, yielded insights into what occurred. This is a region of very complex topography, and the burn was located in another valley away from the population center. The ventilation index was good for the afternoon period in the vicinity of the burn, but was marginal over Salmon. Afternoon trajectories showed smoke from the burn moving directly over the town. While mixing heights during the afternoon were high enough to not cause smoke problems, by 1700 local time the mixing height lowered and winds became calm, setting up conditions to trap smoke in the valleys as the burn continued to smolder into the evening. Analysis of BlueSky indicates that limiting the size of the burn or postponing to a period with more favorable ventilation conditions could have mitigated the impacts on the town and allowed the second day burn to occur. This case example illustrates that forecasting tools such as BlueSky that combine trajectories, $PM_{2.5}$ concentration fields, and meteorological data can be used to refine burn decisions, allowing land managers to accomplish their fuels reduction and ecosystem management goals while mitigating the impacts of smoke on sensitive receptors downwind.

The ClearSky agricultural smoke prediction was created in response to litigation regarding field burning in the northwestern U.S. Health and environmental activists brought suit against government and land owners, contending that smoke harms people both directly and indirectly. The State of Washington took the approach of banning the burning of the KBG stubble and operating a permit system for burning of wheat stubble. Idaho made the legislative finding that burning of KBG stubble is an economic necessity for KBG growers and thus administers a program overseeing such burning. Similarly, the Nez Perce Tribe administers its own smoke management program for field burning. ClearSky is consulted by these agencies as a key tool in their daily burn decision process.

22.5.2. Wildfires

Wildfires and wildland fire managed for resource benefits are naturally occurring or unplanned fires. Although firefighters have limited options for reducing smoke from wildfires, smoke prediction systems can be useful in managing fire operations, alerting the public to potential health risks and informing a public concerned about scenic vistas, recreation, road closures, and air operation impacts. Additionally, in the United States, the need to reintroduce fire into fire-adapted ecosystems after years of fire suppression along with limited fire fighting resources and concerns for fire fighter safety, has led to the concept of appropriate management response (AMR) when managing a wildfire. Under AMR, wildfires are managed by a suite of response options from full suppression to allowing it to burn for resource benefits. Smoke impacts to communities are an important consideration when managing a wildfire project and are monitored throughout the life of the project. Smoke prediction systems aid in this monitoring effort, as exemplified by a wildfire project in 2003 in the California Sierra Nevada. In this case, smoke management specialists were concerned about smoke from the fire entering the Sacramento Valley. By using BlueSky, they were able to ascertain that it was smoke from another fire further north that was impacting the valley, that smoke from their fire was going east over an unpopulated region of Nevada, and therefore mitigation strategies were not needed that particular day on the wildfire project.

Tactical decisions can also be based on smoke predictions. Burnout operations, which are deliberately ignited fires designed to prevent wildfire spread by reducing fuels and providing a fire break at a predetermined location, can be timed to have minimal smoke impacts. This was the case with the Square Lake fire near Leavenworth, Washington, in 2003, where a large-scale burnout (thousands of acres) was delayed because the prevailing winds would have carried the smoke into this tourist town during a holiday. Other tactical decisions include where to focus fire suppression efforts, what degree of effort should be employed, and timing of aircraft operations dependent on visibility.

22.5.3. Regulatory applications of smoke predictions

One application of smoke predictions is to track the source of smoke that may have caused (or could potentially cause) a negative impact. Some systems, such as the Australian system, allow calculation of backward trajectories to show likely source areas for smoke. In Australia, these backward trajectories are used to indicate which fires should not be ignited. Other systems require analysis and interpretation to determine which burns or fires may have contributed to a smoke event. In many cases it is the regulatory agencies that make the decision to allow or disallow burning on any given day. Of particular interest to regulatory agencies is the ability of smoke prediction systems to provide information about cumulative impacts caused by multiple burns. This provides an opportunity to open a dialogue among the various land management agencies about sharing the airshed and minimizing smoke impacts to communities.

22.5.4. Challenges

Development of these applications requires overcoming two important challenges: the collection of input data and the ability to produce a prediction that is timely enough to be useful. We discussed above the challenges associated with ground-based and satellite-based fire activity inputs, such as interagency data consistency issues in the ground-based systems and detection issues with the satellite-based systems. These challenges are being overcome as the two types of fire activity sources are merging to complement each other for the purposes of smoke forecasting.

One important application of smoke prediction systems is to make a go/no-go or tactical decision about a burn based on the potential for smoke impacts to a community or sensitive receptor. Such decisions are generally made early in the morning and require that all model processing be complete and output available to the decision maker by 6–8 A.M. In some cases decisions must be made the day before burning is scheduled, requiring a lead time of 48 h for the real-time smoke prediction system to gather the inputs and provide predictions suitable for decision support.

22.6. The future of real-time smoke prediction systems

The merging of existing fire science and air quality research into these real-time smoke prediction systems is proving useful to the agricultural, land, fire, smoke, and air quality management communities who regard these systems as providing useful guidance based upon the latest available science. Despite the wide application of these systems to prescribed fires, agricultural fires, and wildland fires, significant opportunities for future development remain. Two ways in which the usefulness of real-time smoke predictions can be improved is through advances in how the information is presented and by providing more accurate forecasts.

Users play an important role in how the results from the real-time smoke prediction systems are presented because smoke predictions must be tailored to a region. Some of these differences can be seen in the approaches of the four systems profiled here. BlueSky offers surface $PM_{2.5}$ concentrations as simple animations, and a variety of other meteorological, landuse, $PM_{2.5}$, and trajectory output products are available through the more complex RAINS GIS interface. The ClearSky and Australian systems were developed in close collaboration with a user community who regarded scenario-based output products as providing the best guidance. Therefore, these systems provide smoke concentration data based on where burns are most likely to be ignited and are not designed to capture exact $PM_{2.5}$ concentrations from fire across the region. The NOAA-HYSPLIT and BlueSky systems demonstrate that real-time smoke prediction systems can serve not only the fire community concerned with tactical decisions about fire but also the air quality community concerned about downwind impacts of smoke and all pollutant sources. The NOAA-HYSPLIT smoke prediction system at its inception was designed to be an interim tool until daily fire emissions could be made available to the NOAA national air quality prediction system (Otte et al., 2005), and daily wildfire emissions from BlueSky are being incorporated into the U.S. Pacific Northwest's AIRPACT-3 air quality prediction system (http://www.airpact-3.wsu.edu). BlueSky predictions are also being incorporated into the U.S. EPA's AirNow (http://www.airnow.gov) air quality prediction and monitoring portal. These output products and linkages are continually being updated to reflect the growing and changing needs of the user communities.

The usefulness of smoke predictions can also be improved by improving their accuracy, which involves improving the accuracy of the individual components and integrated field campaigns to obtain evaluation data. Smoke prediction systems are collections of models representing different pieces of information needed to generate the prediction—weather models, fire activity, fuel loading, consumption models, emissions models, plume rise algorithms, and dispersion/trajectory/transport models. Uncertainties are associated with each of the component models, making resulting errors challenging to analyze and diagnose. Yet determination of the uncertainties associated with a given prediction and dissemination of that information to the user community is necessary for these systems to be useful as decision-support tools. Therefore, understanding these uncertainties and how they relate to forecast skill needs to be a top priority of future development.

Evaluation of these systems has shown the importance of incorporating knowledge about fire behavior into the forecasts. Researchers at the USFS Missoula Forest Fire Laboratory (http://www.firelab.org/rsl/beowulf.htm) are working on incorporating the fire area simulator (FARSITE; Finney, 1998) model into a smoke prediction system utilizing the WRF model coupled with chemistry (WRF-Chem; Grell et al., 2005). Fire behavior also affects plume rise which determines the vertical allocation of the fire emissions in the atmosphere, thereby critically affecting overall surface concentrations (Larkin et al., 2008; Liu et al., 2006). Further research and development of methods of incorporating fire behavior into these real-time smoke prediction systems is necessary.

Accurate meteorological forecasts are critical because they determine direction and speed of the pollutant transport. Advances in meteorological forecasts—including ensembling techniques, improved planetary boundary layer schemes and land-surface models, and greater resolution—will improve the quality of the smoke prediction. The ClearSky results have shown that ensembling techniques can directly benefit smoke forecasts and allow for the calculation of the ensemble spread, a measure of forecast uncertainty.

Large fires can create their own fire weather by changing local wind patterns and temperature, and furthermore, emissions from fires can alter the radiative properties of the atmosphere. Clark et al. (2004) describe a fire-atmosphere model that couples fire dynamics with meteorology, where local winds are used to predict fire spread, and then the heat and moisture fluxes from the fire are fed back to the meteorology, allowing the fire to influence the local winds. Linn and Cunningham (2005) and Mell et al. (2007) have developed computational fluid dynamic models that explicitly simulate fuel/flame interactions and plume/atmosphere interactions. In addition, researchers at the Missoula Forest Fire Laboratory (http://www.firelab.org/rsl/beowulf.htm) are working with the WRF-Chem model (Grell et al., 2005) to fully couple the chemical solver within the meteorological model in order to account for atmospheric chemistry effects on the radiation budget and aerosol interactions with cloud formation. While implementation of many of these developments into real-time smoke predictions systems is further in the future, such work resolving fire/atmosphere feedback loops advances fundamental fire science and will eventually be beneficial operationally as computing resources improve.

Additionally, improvements to both ground-based fire tracking systems and satellite fire detection algorithms are necessary. Satellite detection of fire can provide a large-scale consistent data record; however, improvement is needed in the detection algorithms to more accurately detect small fires, remove confounding factors such as clouds, and accurately obtain an area estimate of fire size. Similarly, ground-based fire-reporting systems need improvement to augment and correlate with satellite data, provide the necessary inputs to the smoke prediction systems, and provide consistency across regions, systems, and agencies.

The quantity and type of emissions from fire are a function of the fuel combustion, which is largely driven by the method of ignition, the vegetation type, weather conditions, and fuel moisture. Most emission models, however, do not rely on combustion physics but rather empirical emission factors derived from field studies and therefore cannot represent all burn scenarios and conditions. Improving emissions models to take into account combustion physics, such as being empirically estimated by FEPS (Anderson et al., 2004) and explicitly modeled (Linn & Cunningham, 2005; Mell et al., 2007), is necessary.

Advances in smoke prediction systems will progress faster when more observational data are available to evaluate the systems and component models. Integrated field campaigns that measure trace gases and aerosols from the fire both near-field and far-field, fuel loadings and consumption, and fire spread, are necessary. Furthermore, ground-based measurements are not enough; a three-dimensional analysis of the plume as it advects and undergoes chemical transformation is necessary. Satellite data can also be used to evaluate smoke prediction models, as demonstrated by work done with the NOAA-HYSPLIT system. Research into correlating the column integrated aerosol optical depth satellite measurement with results from the smoke prediction systems is also needed.

The beauty and benefit of the systems profiled here is that each system has taken a different approach to meeting the needs of their users. Fundamentally, however, they all rely on similar fire science and air quality models. Thus, improvements to individual systems have benefits for all. Because of the interdisciplinary nature and scale of the challenges in creating timely, accurate, and usable smoke forecasts, significant advances will be more easily achieved through continued close collaboration regarding specialized field work, understanding of component interdependencies and uncertainties, and creation of new modeling and analysis schemes for plume rise and other critical issues. In this way smoke prediction is becoming a community-modeling enterprise.

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