Development and Applications of Systems for Modeling Emissions and Smoke from Fires: The BlueSky Smoke Modeling Framework and SMARTFIRE

Dana Coe Sullivan, Sean M. Raffuse, Daniel A. Pryden, Kenneth J. Craig,
Stephen B. Reid, Neil J.M. Wheeler, and Lyle R. Chinkin
Sonoma Technology, Inc., 1455 N. McDowell Blvd., Suite D, Petaluma, CA 94954

Narasimhan K. Larkin, Robert Solomon, and Tara Strand
U.S. Forest Service, 400 N. 34th Street, Suite 201, Seattle, WA 98103

ABSTRACT

The BlueSky Framework is a model management system that facilitates ease and flexibility in running third-party models to simulate the cumulative impacts of multiple fires (Larkin et al., 2008). Developed by the U.S. Department of Agriculture-Forest Service (USFS), it facilitates coordinated operation of models to predict emissions from fires and resultant ground-level concentrations of fine particulate matter ($PM_{2.5}$) and other pollutants. The BlueSky Framework has recently undergone significant re-engineering and improvements, and is currently being applied to the U.S. Environmental Protection Agency's (EPA) National Emission Inventory (NEI) for operations supporting real-time air quality predictions, and for a variety of smoke impacts management and planning tools. The re-engineered system is modular, adaptable, and easy to use; and it offers a wide variety of options and models built in.

A major development complementing the re-engineered BlueSky Framework is a system that prepares fire activity data—the Satellite Mapping Automatic Reanalysis Tool for Fire Incident Reconciliation (SMARTFIRE). SMARTFIRE integrates and reconciles fire activity data from multiple information sources—i.e., databases of satellite-detected fires, records of human-reported fires, or other sources. Hence, SMARTFIRE harnesses the advantages of multiple information sources by retaining the value added by each data set while avoiding double counting. Its algorithms apply geographic information to associate proximate fires, define large events or fire complexes, and maintain these associations over time as fire events progress across the landscape, merge, or even divide into multiple fire fronts. SMARTFIRE also estimates the geographic extents of burned areas from satellite data.

INTRODUCTION

From around 1910 through 1970, U.S. wildland managers vigorously pursued well-defined policies calling for the suppression of all wildland fires, safety and resources permitting. Fire suppression programs were extraordinarily effective during this period. Fires on the landscape were substantially reduced—to a degree that is now considered unnatural and unhealthy for the wildland environment. But beginning in the 1970s, policy directives began to shift in response to improving scientific understanding of the role of fire in the natural environment. Today, fire is recognized as a natural force of healthy wildland ecologies—a necessary element in complex cycles of destruction, rebirth, and renewal. However, the historical pattern of fire suppression—though well-intended at the time—produced unforeseen adverse consequences, which continue to affect our natural environment today (Pyne, 1982).

Species and ecologies dependent on fire for the renewal of their lifecycles have fallen into unhealthy states. But perhaps more immediately troublesome is a widespread buildup of combustible woody materials on U.S. wildlands. Never before has the risk of vast, far-out-of-control wildland fires—“superfires”— been greater on U.S. wildlands. Such fires threaten private and public property, lives, infrastructure, treasured national resources, and sites of national heritage. And among the natural resources at risk from catastrophic wildland fires are air quality and visibility resources.

Forest and land managers are actively attempting to mitigate extremely high levels of wildfire risk and restore wildland health by increasing rates of prescribed burning and wildland fire use (WFU) fires. WFU refers to non-suppression practices applied for certain fires occurring in wildland areas. WFU fires are monitored but are intentionally not suppressed, as long as they do not threaten valued resources or threaten to spread wildly out of control. Instead, WFU fires are allowed to fulfill the natural role of fire in wildlands. Prescribed and WFU fires are expected to consume high-risk woody fuels in a safe and controlled manner, thereby eliminating rare-but-inevitable wildfires. The air quality and visibility impacts of prescribed and WFU fires are expected to be cumulatively less severe than those of the wildfires they are meant to prevent. However, the need is clearly growing for timely and complete assessments of smoke impacts. The urgency of this need is compounded by the recent promulgation of new federal air quality standards, which are expected to trigger the re-designation of significantly more areas as non-attainment, and by the enactment of regional haze standards protecting the airsheds of sensitive vistas, such as those of U.S. national parks. Given the scenario of increasingly limited air and visibility resources during a time of increasingly active fire frequency (whether managed or not), forest and land managers and air quality agencies will need access to greater intelligence than ever before to meet their respective missions effectively. Improved assessments of smoke impacts can help support prudent management of prescribed fires, wildland fires, and their associated risks. In addition, they can help guide the development of effective air quality policies balanced against the urgent need to manage wildfire risks.

Assessing smoke impacts from wildland fires presents multiple challenges, such as obtaining the best available fire data, reconciling data from multiple information sources, characterizing fuels, calculating emissions, and predicting plume heights. Distributing the predictions for operational use by burn managers in their daily “go/no-go” decisions raises additional challenges, such as computational time constraints and system and network reliability. Currently, emission inventories and real-time smoke predictions are available across the conterminous United States via BlueSky Framework-enabled operations. The BlueSky Framework modularly links computer models of fuel consumption and emissions, fire, weather, and smoke dispersion into a system for predicting the cumulative impacts of smoke from prescribed fires, wildfires, and agricultural fires. Each night, BlueSky-enabled systems automatically obtain regional meteorological predictions and fire data, merge these information sets with models of fuel consumption, plume rise, and emissions, and process dispersion, trajectory, and photochemical models to produce regional estimates of smoke concentrations for the next 2 to 10 days. BlueSky-enabled systems or products are being incorporated into a variety of air quality and emissions information systems, including the National Weather Service's smoke forecast product, smoke prediction systems of the Fire Consortia for Advanced Modeling of Meteorology and Smoke (FCAMMS), the Northwest's AIRPACT-3 system, the British Columbia and Alberta, Canada, smoke forecasting operations (a collaborative effort of the BC Ministry of Health, University of British Columbia, the Canadian Forest Service, and Environment Canada), and a demonstration of air quality predictions enabled with the Community Multiscale Air Quality (CMAQ) model. In addition, BlueSky-enabled systems have recently been processed retrospectively to generate wildland fire emission inventories and agricultural/rangeland fire activity data for the period September 2002-December 2006 for incorporation into U.S. Environmental Protection Agency's (EPA) National Emission Inventory (NEI).

TECHNICAL OVERVIEW OF BLUESKY SYSTEMS

Satellite Mapping Automatic Reanalysis Tool for Fire Incident Reconciliation (SMARTFIRE)

SMARTFIRE is a system for reconciling multiple sources of fire information into a single coherent data stream. SMARTFIRE's algorithm and database system is built within a geographic information system (GIS) framework. SMARTFIRE was built with the capability to ingest multiple disparate fire reporting data sets to produce a single unified data set. Currently, two input data sources have been implemented within SMARTFIRE: Incident Command Summary reports and satellite-derived information as provided by the NOAA Hazard Mapping System (HMS). However, the system architecture was designed in consideration of accepting additional sources of information in the future, such as interactive manual data entry through a web interface or the Western Regional Air Partnership's (WRAP) Fire Emissions Tracking System (FETS) (see www.wrapfets.org).

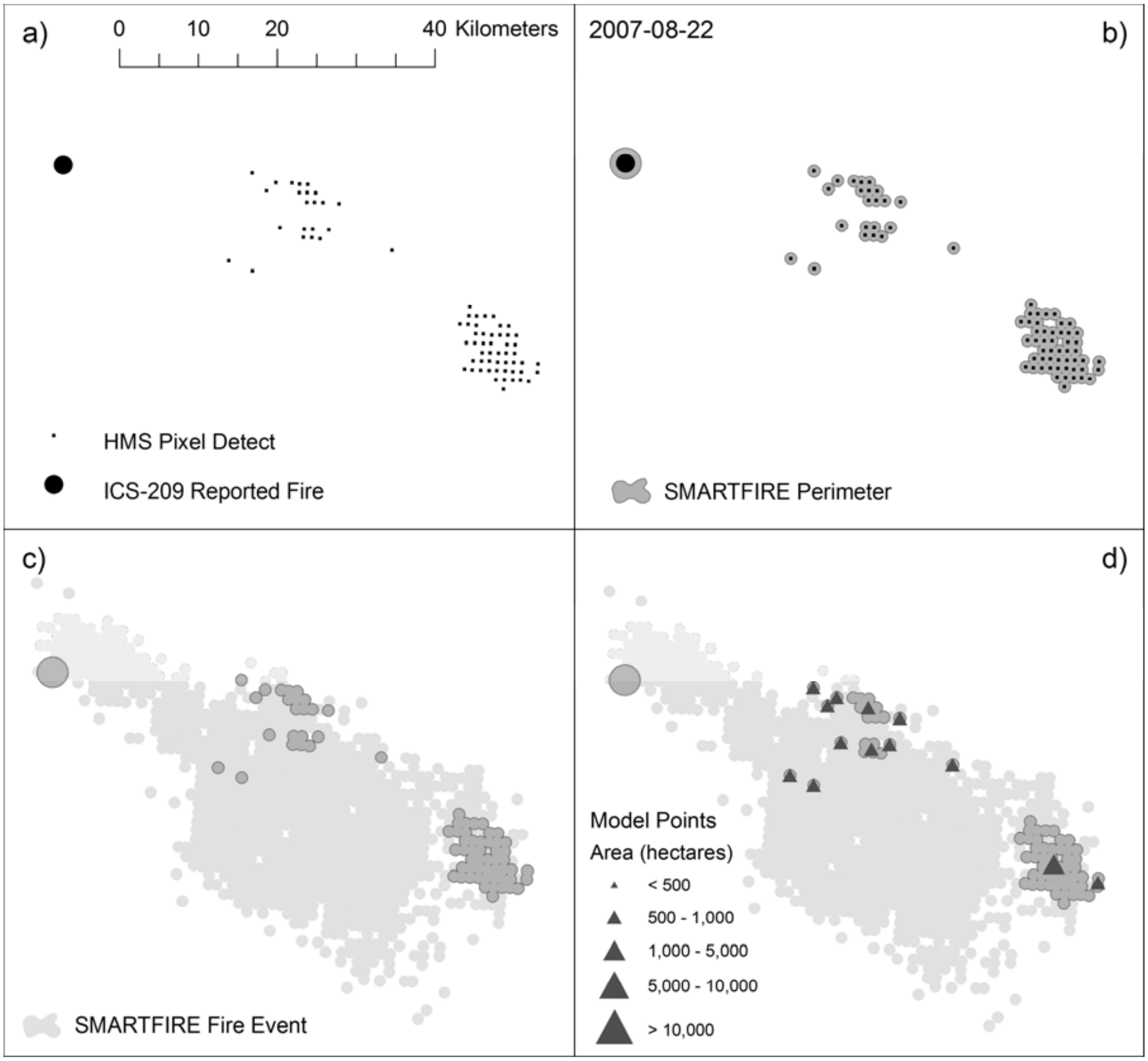
Incident Command System reports (known as ICS-209 reports) are created on a near-daily basis for large wildfires and WFU fires for which there is a federal response. ICS-209 reports contain useful information about particular fires or fire complexes such as descriptions of the fuel loading, growth potential, and type of fire. However, ICS-209 reports also have several limitations. Daily estimates of actively burning areas are required, but ICS-209 reports provide only the ignition point of the fire and an estimate of the total area burned over the lifetime of the fire. For large fires, active flame fronts can move dozens of kilometers from the original ignition point of the burn. More importantly, ICS-209 reports are only created for a small subset of fires. Fires that are not tracked with ICS-209 reports include prescribed burns, agricultural burns, and wildfires for which there is no federal response. Taken together, these missing fires represent a large fraction of the total area burned and resulting smoke emissions. The National Interagency Fire Center (NIFC) reports that at least 9,000 km^2 of prescribed burning has been accomplished each year since 2001 in the United States, representing up to 40% of the total area burned (National Interagency Fire Center, 2006).

The Satellite Services Division (SSD) of NOAA's National Satellite and Data Information Service (NESDIS) produces a daily quality controlled fire and smoke analysis for the United States through the HMS (Ruminski et al., 2006). The HMS integrates satellite data from three instrument—Geostationary Operation Enviromental Satellite (GOES), Moderate Resolution Imaging Spectroradiometer (MODIS), and Advanced High Resolution Radiometer (AVHRR)—aboard seven different satellite platforms. Trained NOAA satellite analysts use the outputs from automated fire detection algorithms as well as various ancillary data layers. The automated fire detection algorithms produce false detections, especially in areas of high surface reflectance, sun glint, or high surface temperature (Hoelzemann et al., 2004; Giglio, 2005). The analysts review fire detects from the algorithms to reduce false detects and scan the satellite imagery to add fires that the algorithms have not detected. (For example, if a smoke plume detected in visible imagery has no associated fire detect, it will be added). The analysis is updated at http://www.ssd.noaa.gov/PS/FIRE/hms.html several times a day. The HMS is described in detail by Ruminski et al. (2006).

The SMARTFIRE algorithm consists of four general steps, outlined for a small area in Figure 1:

1) Daily input data are loaded into the geodatabase.
2) Individual data points are associated together by proximity into Fire Perimeters representing contiguous burning regions.
3) Fire Perimeters are associated to Fire Events by proximity in time and space. Fire Events grow over time as long as the fire continues to be detected and represent the history and progression of the fire.
4) Fire Perimeter polygons are converted to point data for modeling by calculating centroids. For each model point, an area burned is estimated.

Figure 1. SMARTFIRE reconciliation algorithm illustration: (a) input data; (b) fire perimeters; (c) fire event association; (d) model fire points.



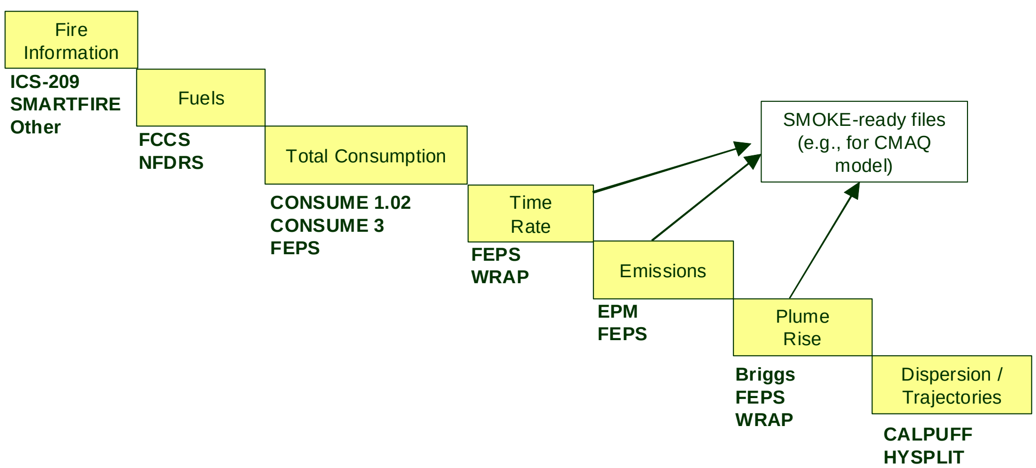
BlueSky Framework 3

The BlueSky Framework is a modeling framework designed to facilitate the coordinated operation of models that simulate cumulative smoke impacts, air quality, and emissions from forest, agricultural, and range fires. The BlueSky Framework allows users to combine state-of-the-science emissions, meteorology, and dispersion models to generate results based on their preferred choices. In other words, the individual steps of existing models have been decoupled as needed, and "wrapper" code has been created such that each model behaves as a module within the architecture of the framework. The outputs of one model are processed and passed as inputs to the next model in the processing chain. The framework will launch any user-selected choice of model at each step. (However, note that the BlueSky Framework is not itself a model. It is simply a model management system, or framework, that offers the architecture for multiple and varied models to communicate with each other in a modular, user-driven environment. It does not estimate emissions or predict concentrations of air pollutants, but it does allow much greater ease in running the models that will do these things.)

Figure 2 illustrates an overview of the built-in processing steps and model choices available within the framework as built, including the following:

- Process fire information inputs, as acquired from SMARTFIRE or local data files.
- If fuels are not specifically defined for a fire, a fuel model is assigned by default according to spatially resolved information.
- Unless fuel consumption is specifically defined for a fire, a fuel consumption model is used to estimate the total mass of fuels consumed.
- The time rate of emissions (hourly) is estimated.
- Emissions are calculated according to emissions models, which assign emission factors calculated in terms of mass emitted per mass of fuel consumed.
- Plume rise is estimated to define the vertical extent of initial emissions distribution.
- Dispersion or trajectories of pollutants as they travel downwind can be modeled.
- In addition, the BlueSky Framework 3 outputs Sparse Matrix Operator Kernel Emissions Modeling System (SMOKE)-ready files, which can be used for input to Eulerian models, such as the CMAQ model. Eulerian models run outside the Framework.

Figure 2. Processing steps and available choices at each step as built in for the BlueSky Framework version 3.



However, it should be noted that the Framework is easily adaptable and extendible, such that new wrapper code can be adapted or added within its existing structure. This allows users to easily implement further processing steps and/or any model choices as desired, in addition to those illustrated in Figure 3. Furthermore, users may implement any subset of the available processing steps and/or in any sequential order desired. (For example, users may stop processing after emissions are calculated.) Currently, most BlueSky Framework implementations use the FCCS fuel-loading map and EPM created by the U.S. Department of Agriculture-Forest Service (USFS) Fire and Environmental Research Applications (FERA) Team, as well as the CALPUFF puff-disperson model (TRC Companies, 2008). However, the National Weather Service uses the BlueSky Framework with the HYSPLIT dispersion model (Air Resources Laboratory, 2008) and STI is currently demonstrating its use for generating daily predictions of $PM_{2.5}$ and ozone with the CMAQ model. The improved modularity, flexibility, and extendibility of the BlueSky Framework 3 have facilitated several recent applications and new research initiatives.

APPLICATIONS OF BLUESKY SYSTEMS

BlueSky-enabled systems have historically been used to support the National Weather Service's national smoke forecast product and the FCAMMS regional smoke prediction systems. Work or discussions are currently underway to incorporate updated systems—SMARTFIRE and the BlueSky Framework 3—with these operations. In addition to these existing applications, several recent and near-future applications of BlueSky systems are now moving forward, made possible by the updated BlueSky systems. These applications include development of the wildland and agricultural fire emission inventories for the EPA's NEI) (Raffuse et al., 2008), demonstration of daily $PM_{2.5}$ and ozone air quality predictions using CMAQ and dispersion models (see www.getbluesky.org), development of the Air Quality Impacts Planning Tool (AQUIPT)—a long-range air impacts planning tool for use in optimizing wildfire risk resource management, and development of web services applications to facilitate studies of uncertainties and model intercomparisons. Perhaps most notably, the BlueSky Framework 3 has been accepted by the Joint Fire Science Program (JFSP) as the basic foundation for a major Smoke and Emissions Model Intercomparison Project—a program modeled after the Intergovernmental Panel on Climate Change's (IPCC) Atmospheric Model Intercomparison Project for forecasting climate change (Gates, 1999, 1992). The SEMIP is intended to help researchers begin addressing the major uncertainties and differences that have been observed when different models, options, inputs, or settings are applied in modeling smoke impacts and fire emissions.

AVAILABILITY OF BLUESKY SYSTEMS AND BLUESKY-ENABLED SERVICES AND PRODUCTS

BlueSky systems, related services and products, and links to BlueSky-enabled applications (such as a link to the National Weather Service smoke forecast guidance product) are currently available through the BlueSky Gateway web portal (www.getbluesky.org). Examples of products available at the BlueSky Gateway include the BlueSky Framework version 3 and a web service for downloading SMARTFIRE data. Works in progress, such as SEMIP and AQUIPT, will be included on the BlueSky Gateway portal as they become available.

ACKNOWLEDGMENTS

The authors gratefully acknowledge NASA for substantial financial support for the development of SMARTFIRE and the re-engineering of the BlueSky Framework. Funding was provided through a NASA cooperative research agreement (cooperative agreement number NN506AB52A; technical contact, Lawrence Friedl, NASA Applied Sciences Program), as well as from the National Fire Plan. In addition, the authors wish to thank our many supporters and collaborators, including Mark Ruminski of NOAA's HMS; Amber Soja of the National Institute of Aerospace; Tom Pace of EPA's Emission Inventory Group; Pete Lahm of the U.S. Forest Service; Susan O'Neill of the Natural Resources Conservation Service; and Tweak Films.

REFERENCES

Air Resources Laboratory (2008) HYSPLIT model. Web page of the National Oceanic and Atmospheric Association, Air Resources Laboratory, Silver Spring, MD. Available on the Internet at <http://www.arl.noaa.gov/ready/hysplit4.html>.

Gates W.L. (1992) AMIP: the atmospheric model intercomparison project. *BAMS* **73**, 1962-1970.

Gates W.L. (1999) An overview of the results of the atmospheric model intercomparison project (AMIP I). *BAMS* **80**, 29-55.

Giglio L. (2005) MODIS collection 4 active fire product user's guide: version 2.2. Prepared by Science Systems and Applications, Inc., Lanham, MD, November.

Hoelzemann J.J., Schultz M.G., Brasseur G.P., Granier C., and Simon M. (2004) Global Wildland Fire Emission Model (GWEM): Evaluating the use of global area burnt satellite data. *J. Geophys. Res* **109** (D14S04).

Larkin N.K., O'Neill S.M., Solomon R., Krull C., Raffuse S., Rorig M., Peterson J., and Ferguson S.A. (2008) The BlueSky smoke modeling framework. *Int. J. Wildland Fire* (accepted).

National Interagency Fire Center (2006) Year-to-date information. Wildland fire statistics web site. Available on the Internet at <http://www.nifc.gov/fire_info/fire_stats.htm>.

Pyne S.J. (1982) *Fire in America: a cultural history of wildland and rural fire*, Princeton University Press, Princeton, NJ.

Raffuse S.M., Sullivan D.C., Chinkin L.R., Gilliland E.K., Larkin N.K., and Solomon R. (2008): Development and sensitivity analysis of wildland fire emission inventories for 2002-2006: *17th International Emissions Inventory Conference, Portland, OR, June 2-5*.

Ruminski M., Kondragunta S., Draxler R.R., and Zeng J. (2006) Recent changes to the Hazard Mapping System. *15th International Emission Inventory Conference, New Orleans, LA.* Available on the Internet at <http://www.epa.gov/ttn/chief/conferences.html>.

TRC Companies, Inc., (2008) The CALPUFF modeling system. Web page of the Atmospheric Studies Group at TRC Companies, Inc., Lowell, MA. Available on the Internet at <http://www.src.com/calpuff/calpuff1.htm>.

KEY WORDS

BlueSky Framework

SMARTFIRE

Fire

Smoke impacts

Model management system