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The BlueSky smoke modeling framework

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Abstract. Smoke from fire is a local, regional and often international issue that is growing in complexity as competition for airshed resources increases. BlueSky is a smoke modeling framework designed to help address this problem by enabling simulations of the cumulative smoke impacts from fires (prescribed, wildland, and agricultural) across a region. Versions of BlueSky have been implemented in prediction systems across the contiguous US, and land managers, air-quality regulators, incident command teams, and the general public can currently obtain BlueSky-based predictions of smoke impacts for their region. A highly modular framework, BlueSky links together a variety of state-of-the-art models of meteorology, fuels, consumption, emissions, and air quality, and offers multiple model choices at each modeling step. This modularity also allows direct comparison between similar component models. This paper presents the overall model framework Version 2.5 – the component models, how they are linked together, and the results from case studies of two wildfires. Predicted results are affected by the specific choice of modeling pathway. With the pathway chosen, the modeled output generally compares well with plume shape and extent as observed by satellites, but underpredicts surface concentrations as observed by ground monitors. Sensitivity studies show that knowledge of fire behavior can greatly improve the accuracy of these smoke impact calculations.

Introduction

Smoke from fire is a local, regional and often international issue that is growing in complexity as competition for airshed resources increases. In the US, a history of fire suppression as well as a changing climate has left many forests vulnerable to large wildfires (Pyne 1982; Westerling *et al.* 2006) that are capable of causing air quality impacts detectable at continental scales and beyond, even crossing oceans (Wotawa and Trainer 2000). Additionally, under the US National Fire Plan (USDA–USDI 2000), the use of managed burns is on the rise for hazardous fuels reduction and forest health. Meanwhile, public acceptance of adverse air quality conditions is decreasing, and, in many places, air quality regulations are tightening (Stephens and Ruth 2005). These competing interests are likely to cause potential friction among land managers, farmers, air regulators, and the public.

Fire is an essential ecological process in forested and rangeland ecosystems (e.g. Frost 1998; Pyne 2001), and managing fire is an important component of wildland and agricultural ecology and economics. Forest managers in the US are increasing their use of fire – both managed natural wildfires as well as specially lit prescribed burns – to lessen the risk of catastrophic wildfires by reducing built-up hazardous fuels and to increase forest ecosystem health by re-establishing and maintaining the natural fire regime. For example, during the most recent decade, total US prescribed fire acreage increased by over a factor of three: from less than 4000 km^2 in 1998 to over 12 000 km^2 in 2007, according to the US National Interagency Fire Center (http://www.nifc.gov, accessed 2 October 2009). Additionally, agricultural residue burning is part of the typical practices of many farming communities. In part owing to an expanding wildland–urban interface, many of these burning activities can potentially impact sensitive populations such as children, asthmatics and the elderly, as well as sensitive, protected ecosystems. In order to maximize the ability of land managers and farmers to use planned burning activities for ecological health and crop productivity while at the same time avoiding adverse air quality impacts, an increased understanding of the effects of these activities is needed.

Complicating management of burning activities is a decreasing public and regulatory tolerance for smoke. Lawsuits to protect air quality have been filed in several US states, with negative implications for agricultural and wildland burning (e.g. Spokane Co. 2003). Regulations governing total air quality are tightening, causing emissions from burning to compete with other pollution sources. For example, the US Environmental Protection Agency (EPA; see the Appendix table for a complete list of acronyms, models, and websites) recently reduced the national

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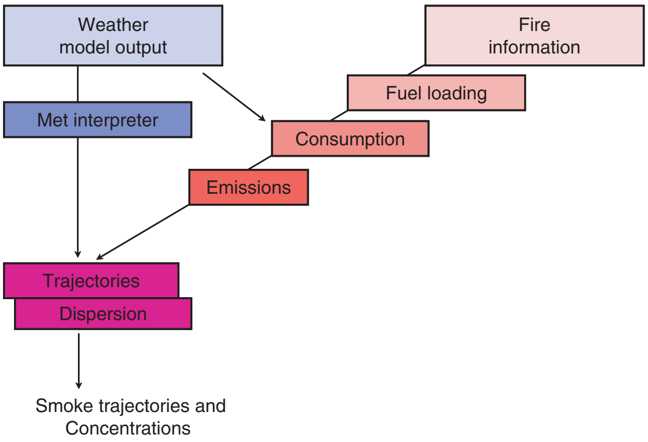

Fig. 1. BlueSky smoke modeling framework model progression. Weather model output and fire information (top) is run through a sequence of modeling steps in order to generate smoke trajectory and concentrations.

ambient air quality standards (NAAQS) for both fine particulate matter ($<2.5\ \mu m$, $PM_{2.5}$) and ozone (O_3). In addition, the 1999 US regional haze rule (EPA 1999*a*) extended special air quality protections to certain natural wildland areas and heritage sites, such as designated National Parks and Wilderness Areas, including protection against visibility impairment from regional haze, which in many regions is largely due to smoke from fires (Grand Canyon Visibility Transport Commission 1996; EPA 1999*a*).

In this increasingly restrictive environment, activities that adversely impact air quality, such as burning activities, must negotiate and compete for limited and decreasing allowable airshed impacts. Increased understanding of the causes and processes of smoke and its impacts are necessary to enable such discussions. In the land management community, it is becoming widely accepted that there is an urgent need for decision-support tools that incorporate the latest scientific knowledge to aid managers in understanding the impacts of fires on air quality.

The BlueSky smoke modeling framework described here is such a tool. Modeling emissions, transport, and chemistry of smoke from fires is complex. It requires a series of processing steps, containing datasets or individual component models, sequentially linked together, starting with fire information and fuel loading, progressing to fuel consumption, and ending with smoke emissions or smoke transport. BlueSky is not a 'model' in the traditional sense; it is a modular framework that integrates existing datasets and models into a unified structure. In doing so, BlueSky can be and has been implemented to create smoke forecasts and decision-support information.

BlueSky's modeling steps are designed to answer a sequence of questions that end with smoke impacts (Fig. 1):

(1) Where and how big are the fires?
(2) What is the fuel available to be burned?
(3) How much fuel is consumed?
(4) What emissions are produced?
(5) Where do the emissions go?

One of the difficulties with such a system is that there are many different models that can be used to answer each of these questions; by incorporating as many models as possible, BlueSky provides the greatest flexibility to the user and also enables direct model-to-model comparisons. Run as a complete system, it needs only meteorological data and fire location and size to produce smoke concentrations and trajectories, but it will also make use of any additional available information provided as input. Component models are run only to produce additional information not already provided. Newer models are easily incorporated, allowing it to keep pace with the state of the science. Open-source-style community development enhances this capability.

BlueSky was originally developed to provide information for forest managers trying to decide if or when to light a prescribed burn. As such, it has been designed to operate quickly in a real-time forecast mode. Because of BlueSky's flexibility, it has found application in a variety of research studies and predictive tools. Currently, BlueSky smoke predictions from wildfires are available daily across the contiguous US through the US Forest Service (USFS)-based Fire Consortia for the Advanced Modeling of Meteorology and Smoke (FCAMMS, http://www.fcamms.org, accessed 2 October 2009). BlueSky-computed emissions are also used in the US National Weather Service's operational smoke forecast products (Rolph *et al.* 2009) and in the daily air quality forecasts for the US Pacific Northwest (Chen *et al.* 2008*a*). Other researchers have used it to help calculate US and global emissions inventories for modeling studies (McKenzie *et al.* 2006; Wiedinmyer *et al.* 2006; Chen *et al.* 2008*b*) and as a fire emissions calculator for other modeling systems (e.g. Pouliot *et al.* 2005).

The present paper introduces the BlueSky framework and describes its technical aspects. We first present the implemented component models and structure as of BlueSky Version 2.5. Predictive and decision support applications using BlueSky are then discussed. The capability of BlueSky to compare model pathways and their interactions and resulting uncertainty is shown through the use of two case studies. Finally, the *Summary* section describes the current status and ongoing development of BlueSky and highlights the changes currently under way for Version 3 and beyond.

Framework structure and methods

Overview of framework

The sequentially linked processing steps used in the BlueSky framework are required to simulate smoke emissions, transport, and chemistry (Fig. 1). BlueSky can be run piecemeal, but to run through the full framework, BlueSky requires two types of information: (1) meteorological information, specifically information on the full four-dimensional (x,y,z,t) evolution of the atmosphere; and (2) basic fire information, specifically fire size (e.g. hectares) and location (latitude and longitude). Although BlueSky does not need any other information to run, additional information provided as input is treated preferentially and will overwrite what BlueSky can otherwise obtain through models or default datasets. For example, if fuel loadings are provided, these will be used instead the fuel loading maps contained in the framework.

Once the fire information is fed into the framework, fuel loadings and moisture conditions are determined, consumption is calculated, and the emissions from the consumption are speciated and allocated diurnally. These emissions then drive the dispersion and trajectory models.

The framework is self-documenting. As it runs, it records each step and its output in a log file. In addition, the entire working directory structure, compiled model executables, and files can be saved for examination or archiving.

The models contained in the framework use both C and FORTRAN code. The framework itself uses PERL and some C and Java. However, a transition is being made to Python for Version 3.0. The BlueSky framework is designed to run on standard LINUX installations, but can be ported easily to any UNIX variant.

Modularity

The BlueSky framework is modular, which allows for great flexibility. Each modeling step in the chain in Fig. 1 can be implemented in a variety of ways using a variety of existing models. To facilitate this, the BlueSky framework is defined in terms of interfaces between the model types (Fig. 2). Because of this, the framework can be started and stopped at any interface point, allowing subsets of the framework to be used without the need to run the rest of the framework. Two file standards are used in the interfaces – the simple text comma separated values standard (CSV) and the binary gridded Unidata NetCDF standard (Rew *et al.* 1997).

Data flow through the framework to and from the currently implemented component models is executed by a wrapper that also translates the data from the interface standard into the specific input required by the component model and similarly translates the model output into the next interface standard (Fig. 2). This modularity allows for ease of implementation of additional models and advances in model components, and inter-model comparison at each level of the framework. The specifics of the available component model choices are described in the following sections.

Meteorological inputs

BlueSky requires three-dimensional (x,y,z) gridded meteorological data on an hourly time step in order to run the dispersion and trajectory models. Currently, BlueSky can easily use model output from a variety of models including the National Center for Atmospheric Research/Penn State Mesoscale Meteorological Model (MM5) Version 3 or later (Grell *et al.* 1994), or its successor, the Weather Research and Forecasting (WRF) model (Skamarock *et al.* 2005).

Fire inputs

The minimum fire information input data required by BlueSky are fire location and daily fire growth. Additional fire information needed is either supplied by a collection of user-modifiable default values or produced by the component models. Any additional information about the fire, such as fuel loadings, fuel moistures, or fire type, included as input are carried through the framework and used preferentially, replacing the default or modeled values.

The fire information can be entered in a standard format simple text (CSV) file. For forecast purposes, automated scripts can be developed to download information from fire reporting systems and translate the information into the standard format text file. Currently, the BlueSky framework offers automatic connection to a variety of systems as shown in Table 1, which reflects BlueSky's history of development in the US Pacific Northwest.

BlueSky is connected to prescribed-burn reporting systems across the US Pacific Northwest (Table 1) including RAZU (Montana, Idaho), FASTRACS (Washington, Oregon), SMOKEM2 (Washington), and ODF (Oregon). Additionally, BlueSky is connected to Washington State University's ClearSky agricultural burning forecasting system (Jain *et al.* 2007) to obtain agricultural burn information on Washington and Idaho wheat stubble and grass seed burning operations. One issue of particular note with respect to prescribed and agricultural burn smoke forecasting is that not all planned burns are actually lit. Where possible, BlueSky obtains not only planned burn information for the future, but also updates its information on past burns from accomplishment reports. These are then used to re-initialize each forecast by spinning up the current state of the atmosphere using only the accomplished burns. BlueSky can also receive wildfire reports from British Columbia.

The newest fire information system to which BlueSky has been connected is the specially developed SMARTFIRE (Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation) system that reconciles satellite data and ground-based reports. SMARTFIRE currently uses the NOAA Hazard Mapping System (HMS) human-quality assured satellite fire detections that are derived from multiple satellites (Ruminski *et al.* 2006) as well as the ground-based US national wildfire and wildland fire use reporting system – the Incident Command System (ICS)-209 reports. SMARTFIRE replaces a previous direct connection to the ICS-209 system. Work is under way to also incorporate prescribed burn reporting systems into the SMARTFIRE system for reconciliation with satellite observations.

Fuel loadings

Fuel loadings for each fire location are needed in order to continue through the BlueSky modeling pathway. When available, these fuel loadings are obtained from the fire activity input data; otherwise they are acquired via fuel map reference tables in BlueSky's fuel loading process step. The default fuel map is from the Fuel Characteristic Classification System (FCCS) (McKenzie *et al.* 2007); other implemented options are from the US National Fire Danger Rating System (NFDRS) (Cohen and Deeming 1985), and the revision by Hardy *et al.* (1998). All of the maps are resolved on a 1-km grid.

The FCCS is a fuel loading classification system based on Bailey ecoregions and satellite-derived cover type, and has been mapped to the contiguous US. It has a detailed six-layer description of vegetation incorporating 16 categories of fuels (duff, litter, grass, shrub, trees, woody debris by size, etc.). The design of the FCCS system allows for emission estimates from all phases of fire (smoldering, surface fire, and crown fire). Efforts are under way to extend the FCCS to cover North America. The NFDRS fuel map is also available over the contiguous US but emphasizes the smaller fuel size classes because, as a system, it was designed to address fire danger (where fine fuels are most important), not total consumption (where larger fuels can be

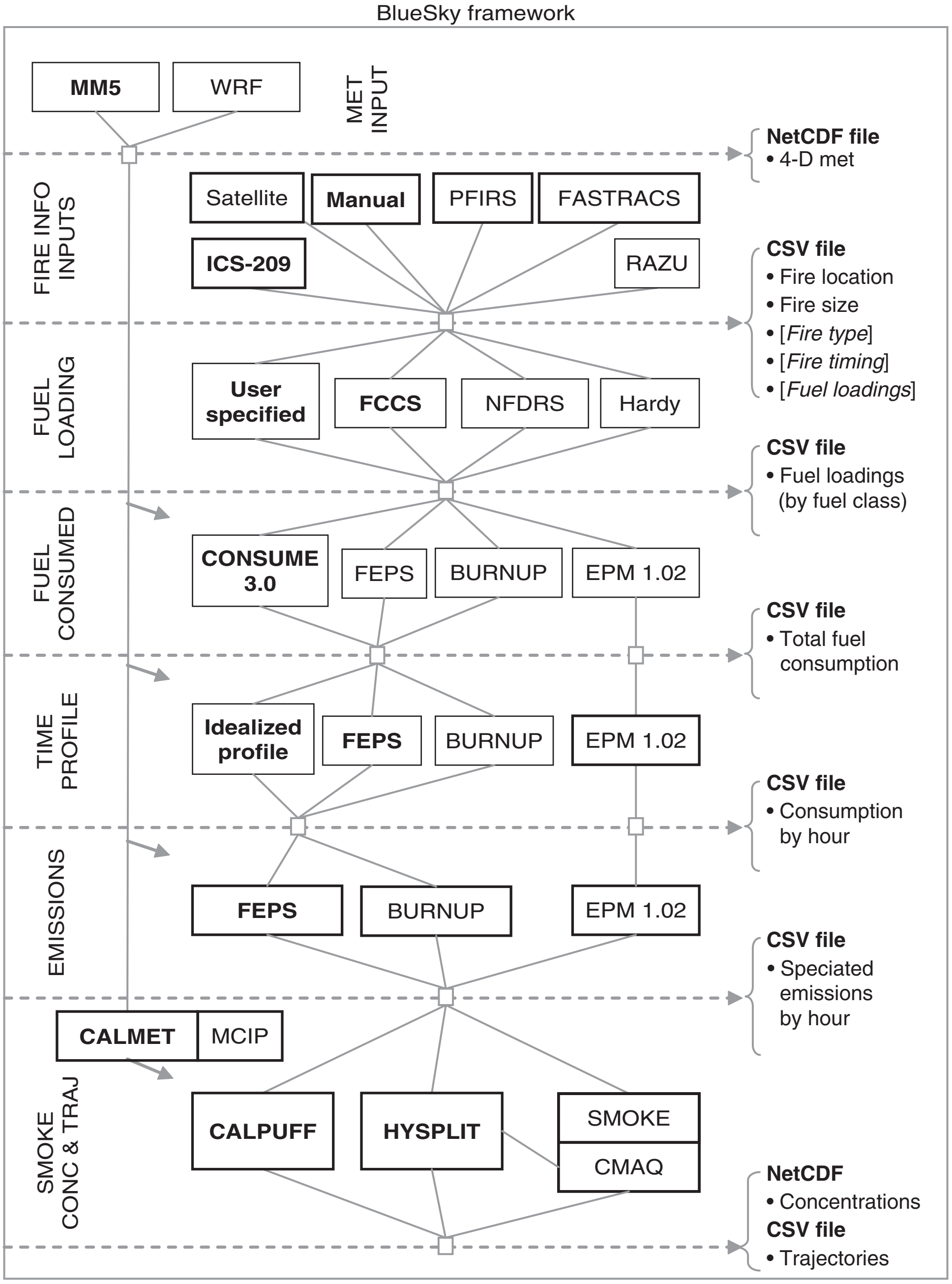

Fig. 2. BlueSky component models and data flow for Version 2.5. Model progression is top to bottom, through the model steps listed on the left. Interface points where the framework can be started or stopped are shown by dashed lines, with the type of file and contained information listed to the right. Implemented models are shown, with the data flow between them indicated by lines. At each step, multiple model choices are implemented. Meteorological data local to the fire are used in several steps. Full meteorological grids are used for trajectory and dispersion calculations. See text for details.

more important). The Hardy *et al*. (1998) fuel map is an update to the NFDRS map for the western US designed to address this problem by providing more realistic fuel loadings in the larger fuel size classes, thereby sometimes significantly increasing the overall fuel loading (see the Case studies section for an example). Some regions mapped by LANDFIRE (http://www.landfire.gov, accessed 2 October 2009), a very-high-resolution (30-m) fuel mapping effort in the US, have also been incorporated into BlueSky.

Total consumption

After fire location, size, and fuel loadings are known, fire consumption for every unit area burned can be determined. BlueSky splits the consumption step into two pieces: total consumption

Table 1. Fire information inputs that have been connected to BlueSky
See Appendix for definitions

Name	Region	Type
Manual	Any	Standard CSV input file fire information
SMARTFIRE	North America	Satellite fire detections (currently NOAA HMS satellite detections) reconciled with ground reports (currently US ICS-209 wildfire reports)
ICS-209	US	Incident command team reports on US wildfires
BC	British Columbia, Canada	Daily wildfire activity data for BC, Canada
ClearSky	US Pacific Northwest	Agricultural burns on private, and tribal lands in Washington and Idaho
RAZU	Montana/Idaho, US	Forest prescribed burning reporting system run by the Montana/Idaho Airshed Group
FASTRACS	Oregon/Washington, US	Forest prescribed burn reporting system for Federal burns
ODF	Oregon, US	Forest prescribed burn reporting system run by the Oregon Department of Forestry
SMOKEM2	Washington, US	Prescribed burn reporting system run by the Washington Department of Natural Resources

and the time rate of consumption. Total fire consumption is calculated because it is most easily measured: using field plots before and after the fire make this step more accurate and verifiable than the hourly time rate of consumption. Total consumption calculations are done separately for each day's fire growth.

The default pathway in BlueSky uses the CONSUME model Version 3 (see *Appendix*) for the consumption calculations. CONSUME was developed empirically from 106 pre- and post-burn plots covering a variety of vegetation types and fire conditions. CONSUME is widely used by US land managers to estimate post-burn consumption for wildfire and prescribed burn reporting purposes. BlueSky can also use the EPM (Emissions Production Model; Sandberg and Peterson 1984) to calculate fuel consumed. EPM internally relies on a simplified version of the CONSUME equations. Similarly, FEPS (Fire Emissions Production Simulator; see *Appendix*), an update to the EPM model, is available, but also uses relatively simple equations based on those in CONSUME. Additionally, the BURNUP model, which is the consumption portion of FOFEM (First Order Fire Effects Model; Reinhardt *et al.* 1997) can be used. CONSUME, EPM, and FEPS, as well as FOFEM, differ in what they allow for input, the assumptions they make for unavailable input, and the way they characterize fuel loadings. Conversion between different types of input is handled by the BlueSky module wrappers developed for each model. Some of these models were originally developed to model prescribed burns although recent versions (such as CONSUME v3) have addressed areas of concern such as crown burning during wildfire events.

Time profile of consumption

Once the total amount of fuel consumed is calculated, the consumption is allocated over time using a time profile. All of the models for this step use relatively simple, idealized profiles or curve fits for this purpose. For a wildfire, the default time profile is from the Western Regional Air Partnership's wildfire profile (Western Regional Air Partnership and Western Governors Association 2005), which allocates 68% of the emissions to an afternoon active fire period (1300–1700 hours local time), but also contains a smoldering component that continues throughout the night. For a prescribed burn, the internal equations in EPM or FEPS (default) can be used, which are based on simple rise and decay curves. FEPS also includes a long-term low-level smoldering component.

Emissions by species

Three emissions models are integrated or are being tested for integration into the BlueSky framework: EPM, FOFEM, and FEPS. BlueSky is most often used to model fine particulate matter with aerodynamic diameters less than 2.5 μm ($PM_{2.5}$), however, several other chemical species are also available through these emissions models. EPM calculates emissions of CO, CO_2, CH_4, total PM, PM_{10}, $PM_{2.5}$, NO_x, SO_2, NH_3, and non-methane hydrocarbons (NMHCs) based on vegetation type. EPM did not originally include NO_x, SO_2, and NH_3 emission factors; thus it was modified to include these species from Battye and Battye (2002). FEPS calculates emissions of CO, CO_2, CH_4, and $PM_{2.5}$ based on combustion efficiency of the burn. BURNUP calculates emissions of CO, CO_2, CH_4, PM_{10}, $PM_{2.5}$, NO_x, and SO_2 based on burn phase (smoldering *v.* flaming) and combustion efficiency. Heat released, necessary for plume rise calculations, is calculated by each of these models and is passed from the emissions module to the following modeling steps.

Dispersion and trajectories

The default dispersion model is the CALPUFF (Scire *et al.* 2000*a*) two-dimension Lagrangian Gaussian puff model. CALPUFF is designated by the US EPA as a regulatory model of choice for simulating pollutant impacts on regional air quality, typically from point sources, but CALPUFF is also capable of simulating area, line and volume sources. BlueSky uses CALPUFF to calculate surface concentrations of smoke, currently $PM_{2.5}$. Owing to its two-dimensional nature, CALPUFF cannot be used to examine concentrations in the vertical layers of the atmosphere. In the BlueSky framework, CALPUFF is set to simulate fire as a buoyant area source, taking into account effects of vertical wind shear, large initial plume size, and density differences between the plume and ambient air. CALPUFF treats smoke as a collection of puffs that are advected downstream, and surface concentrations are computed by calculating each puff's contribution to the total concentration at a point. CALPUFF requires a mass-conserving meteorological field, which is produced using the CALMET preprocessor (Scire *et al.* 2000*b*). CALMET has the option to incorporate meteorological station- and vertical-sounding observations; however, this is not currently used in BlueSky forecast mode. When detailed topography data are available, BlueSky will use the CALMET

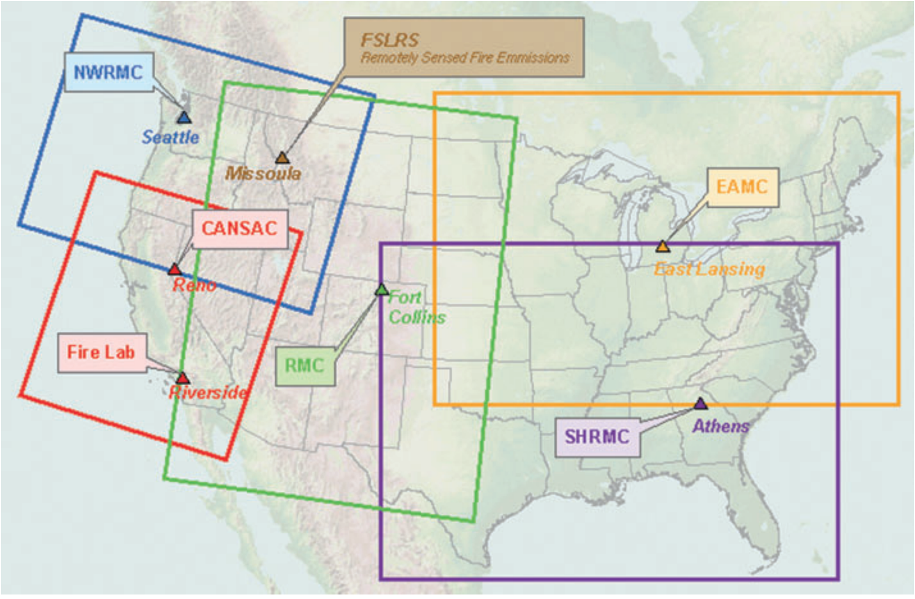

Fig. 3. Fire Consortia for the Advanced Modeling of Meteorology and Smoke (FCAMMS) regions. The five FCAMMS domains are shown along with the locations and names of the seven FCAMMS centers. BlueSky predictions are available daily for each FCAMMS region at http://fcamms.org (accessed 2 October 2009). FCAMMS include the Northwest Regional Modeling Center (NWRMC), the Fire Sciences Laboratory for Remote Sensing (FSLRS), the Eastern Area Modeling Center (EAMC), the Southern High Resolution Modeling Center (SHRMC), the fire lab in Riverside, and the Californian and Nevada Smoke and Air Committee (CANSAC).

downscaling capability to adjust the meteorological field to account for fine-scale terrain effects.

Trajectories are simulated using the HYSPLIT (Draxler and Hess 1997) Lagrangian three-dimension particle-puff model. Twelve-hour trajectories are computed from each burn location. Trajectories, while not taking into account fire heat released or plume rise, do provide a three-dimensional view of where neutrally buoyant plumes could travel in the atmosphere. HYSPLIT can also be used to model the smoke dispersion.

As an alternative to CALPUFF and HYSPLIT, BlueSky emissions can also be incorporated into the Sparse Matrix Operations Kernel Emissions (SMOKE) preprocessor used by the Community Multiscale Air Quality (CMAQ) model (EPA 1999*b*; Byun and Schere 2006). CMAQ is a Eulerian grid one-atmosphere model that incorporates advanced atmospheric chemistry cores. CMAQ is typically run using emissions inventories that incorporate non-burning sources such as anthropogenic point sources and area sources, biogenic volatile organic compounds (VOCs), road dust, and mobile emissions. As of SMOKE Version 2.2, BlueSky output can be read directly by SMOKE, allowing it to be incorporated into CMAQ runs. SMOKE uses a modified form of the Briggs algorithm (Briggs 1975) to calculate plume rise from fire in order to allocate emissions vertically in the atmosphere as discussed in Pouliot *et al*. (2005).

Applications

The BlueSky framework has been implemented, in part or whole, in several experimental prediction products (Chen *et al.* 2008*a*; Rolph *et al.* 2009), and in several different research studies (McKenzie *et al.* 2006; Wiedinmyer *et al.* 2006; Chen *et al.* 2008*b*). The wide range of applications is partially due to the modular nature of BlueSky, which allows for portions of the framework to be used without implementing unneeded components.

Currently, daily BlueSky-based predictions of surface $PM_{2.5}$ concentrations from wildland fires and, where available, prescribed burning and agricultural fires are available across the contiguous US. Official, operational smoke forecasts produced by the US National Weather Service use a custom BlueSky installation as an emissions calculator for fires before processing through HYSPLIT (Rolph *et al.* 2009). Experimental predictions of wildland fire smoke at higher resolution are available on a regional basis (Fig. 3) through the FCAMMS, regional consortia developed based on the model of the Northwest Regional Modeling Consortium (NWRMC; Ferguson 2003; Mass *et al.* 2003) and seed-funded by the US Forest Service through the National Fire Plan. Additionally, wildfire emissions are processed through BlueSky into a format for input into SMOKE used in the AIRPACT3 (Vaughan *et al.* 2004; Chen *et al.* 2008*a*) air quality forecast system operational for the US Pacific Northwest. Further implementations of the BlueSky framework are under way for use in British Columbia and Alberta, and in a national US CMAQ forecast system, the first to include fire emissions.

Graphics of BlueSky output can be produced by any NetCDF-capable visualization program. In addition, BlueSky contains scripts for creating Google Earth readable KMZ files (Fig. 4). These include layers with both fire and smoke information, including ground concentration maps for each modeled hour.

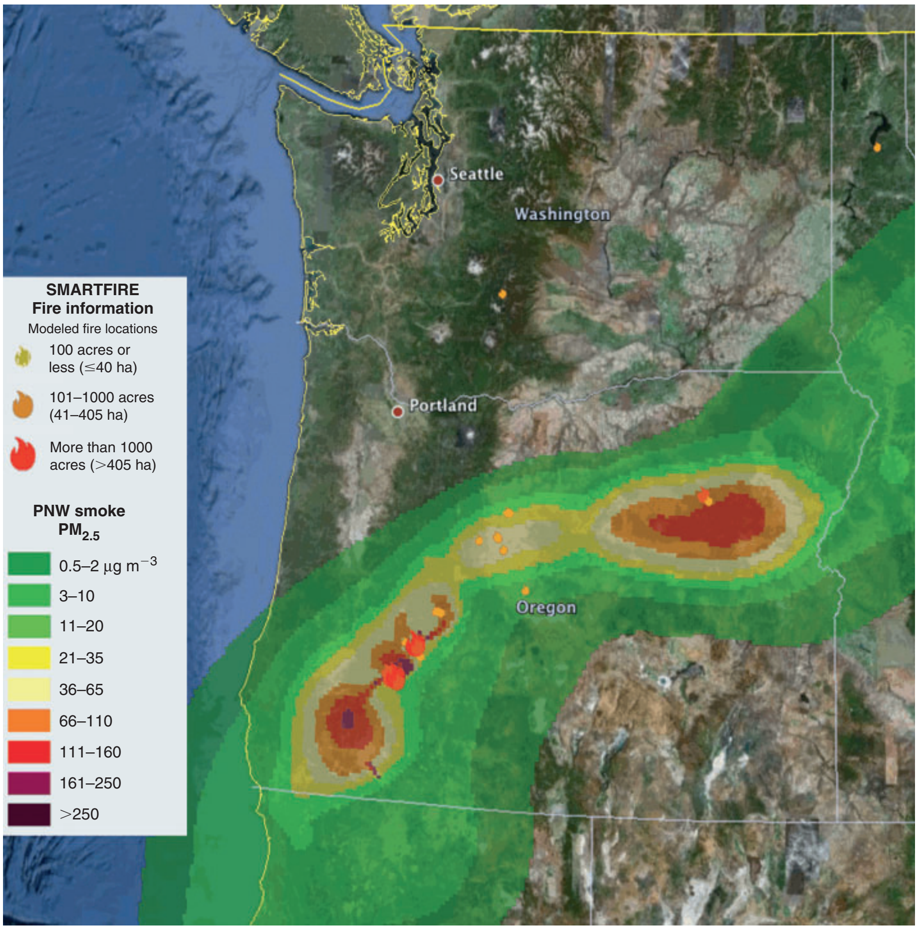

Fig. 4. Smoke prediction output as enabled by the BlueSky framework. KMZ layer output created from the Northwest FCAMMS 4-km domain showing the 24 September 2009 (2000 hours local Pacific Daylight Time) forecast generated from the 23 September 2009 00Z model run. Shown in Google Earth. Both fires (from the SMARTFIRE data feed) and predicted $PM_{2.5}$ surface concentrations are shown. Users can animate the forecasts, zoom, pan, and overlay the forecasts with other KMZ enabled data layers. Many additional layers are available.

Case studies

The BlueSky framework is an integrative modeling tool: it combines many different models to produce the end result. As such, it inherently integrates the state of knowledge of fuels, fire, emissions, and smoke transport and chemistry contained within those models. This makes BlueSky performance critically dependent on the choice of model pathway (for example, over 300 possible pathway combinations are available in Version 2.5).

Indeed, much of BlueSky's utility lies in being able to directly assess the uncertainty associated with choosing one pathway versus another. Because BlueSky incorporates many of the state-of-the-art models in these fields, case studies that compare BlueSky model pathways and highlight the areas of largest model-to-model variability can show where our current understanding is most uncertain and most in need of further research. To demonstrate model pathway variability and uncertainty, we concentrate here on two case studies – the Rex Creek wildfire of 2001 in Washington State, and the Frank Church wildland fire-use complex of 2005 in Idaho (Fig. 5). (Wildland fire-use fires are naturally occurring wildfires that are allowed to burn without suppression as long as specific criteria are met.) The results presented here are intended only to be representative; they need more comprehensive study before they can be considered definitive.

About the fires

The Rex Creek fire was an isolated wildfire that occurred on the eastern side of the Cascade Mountain range in Washington State, ~64 km north-west of the town of Wenatchee (Fig. 5). It burned 182 km^2 (45 000 acres) in August–September 2001, becoming the largest wildfire in Washington State that year. Smoke from the fire heavily impacted the nearby towns of Twisp and Chelan, resulting in multiple days of NAAQS $PM_{2.5}$ limits being exceeded (24-h average $>65\,\mu g\,m^{-3}$, the US EPA standard in effect at the time). The Frank Church complex was a wildland fire-use fire that burned 178 km^2 (44 000 acres) in the Rocky Mountain range in Idaho, west of Salmon, in August–September 2005. Unlike the Rex Creek case, the Frank Church

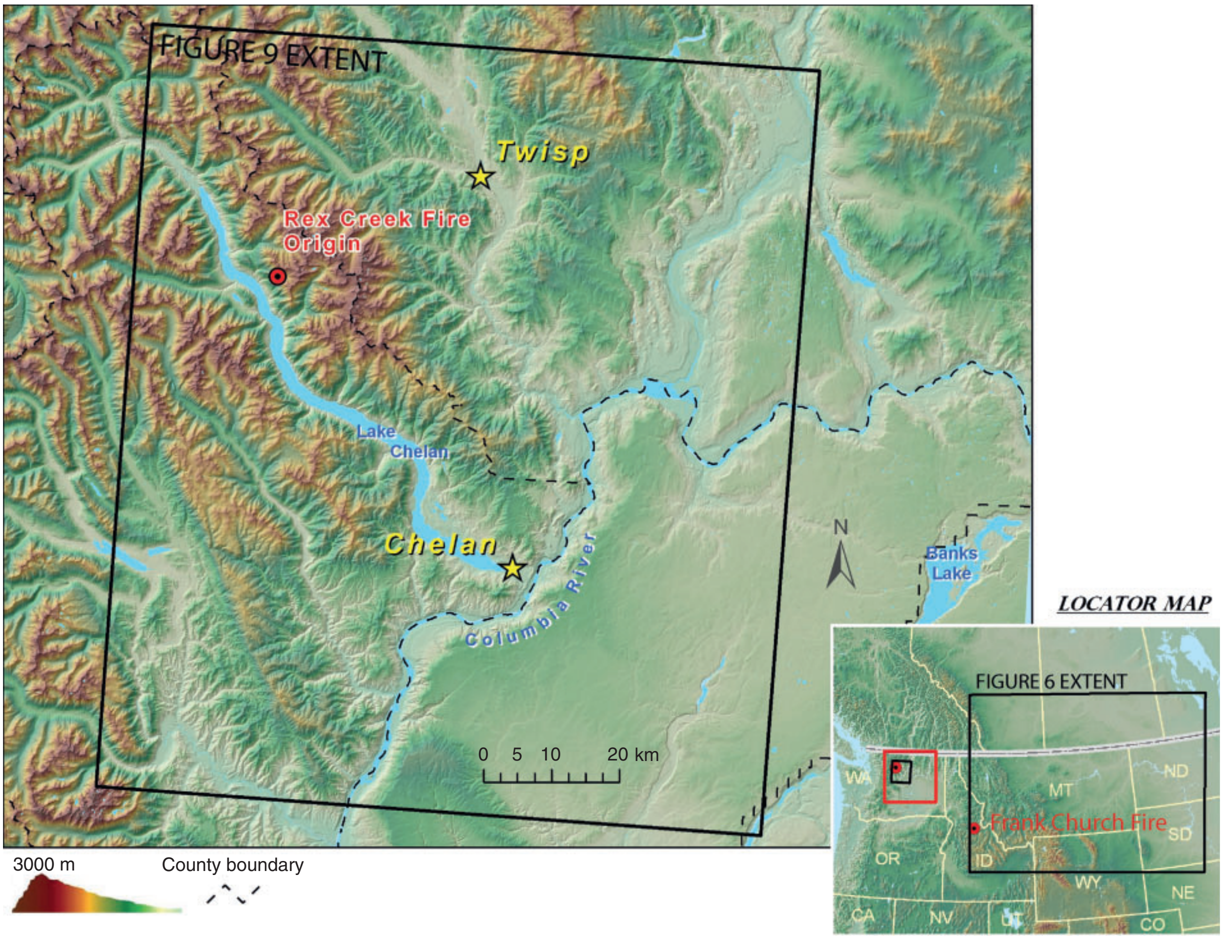

Fig. 5. Map of Pacific Northwest region with terrain shading. Area of Rex Creek fire is shown on detailed map with towns of Twisp and Chelan, Washington; area of Frank Church fire is shown on large-scale map. Fire locations indicated by red dots. Black boxes indicate extent of Figs 6 and 9.

complex was not isolated, but burned during a period of considerable fire activity with many fires burning upwind in Washington and Idaho.

Inputs used

As might be expected, modeled results using BlueSky are heavily influenced by the quality of the input data including the performance of the meteorological model and the estimates of the fire size and location. If the wind is in the wrong direction or if the fires are misplaced, the modeled smoke impacts will necessarily be in error. To reduce input error, we have obtained the best available meteorology and fire information for these case studies. Meteorology from the FCAMMS forecasts was used. For Rex Creek, the 4-km MM5 model output was downscaled to 1-km using CALMET to better resolve the complex terrain. For Frank Church, the 12-km Rocky Mountain Center FCAMMS grid was used. Fire activity for Rex Creek was obtained from the detailed fire perimeter information from the incident command (IC) team. Fire activity for the Frank Church and concurrent fires were obtained from the IC teams where possible, and from the ICS-209 reports otherwise.

Models and pathway used

Because there is no *a priori* reason to choose one model pathway within BlueSky, we examine the variability in the output resulting from varying the model pathway choice. An initial framework pathway was set up using the consumption and emissions calculations of the EPM model, the Western Regional Air Partnership (WRAP) time profile, and the CALPUFF dispersion model. Medium-density pine fuel loadings from the Hardy model were used for Rex Creek and ponderosa pine savannah from the FCCS model was used for Frank Church. From this inital pathway, we then varied the fuel loading, consumption, and emissions models, while holding all other model choices constant.

The large scale

Because more satellite data are available, the Frank Church fire is used to examine the large-scale performance. Simulated $PM_{2.5}$ surface concentrations from the Frank Church complex show a plume extending generally eastward from the main complex with a north–south wavelike pattern (Fig. 6*a*), with the highest concentrations occurring near the North Dakota–South

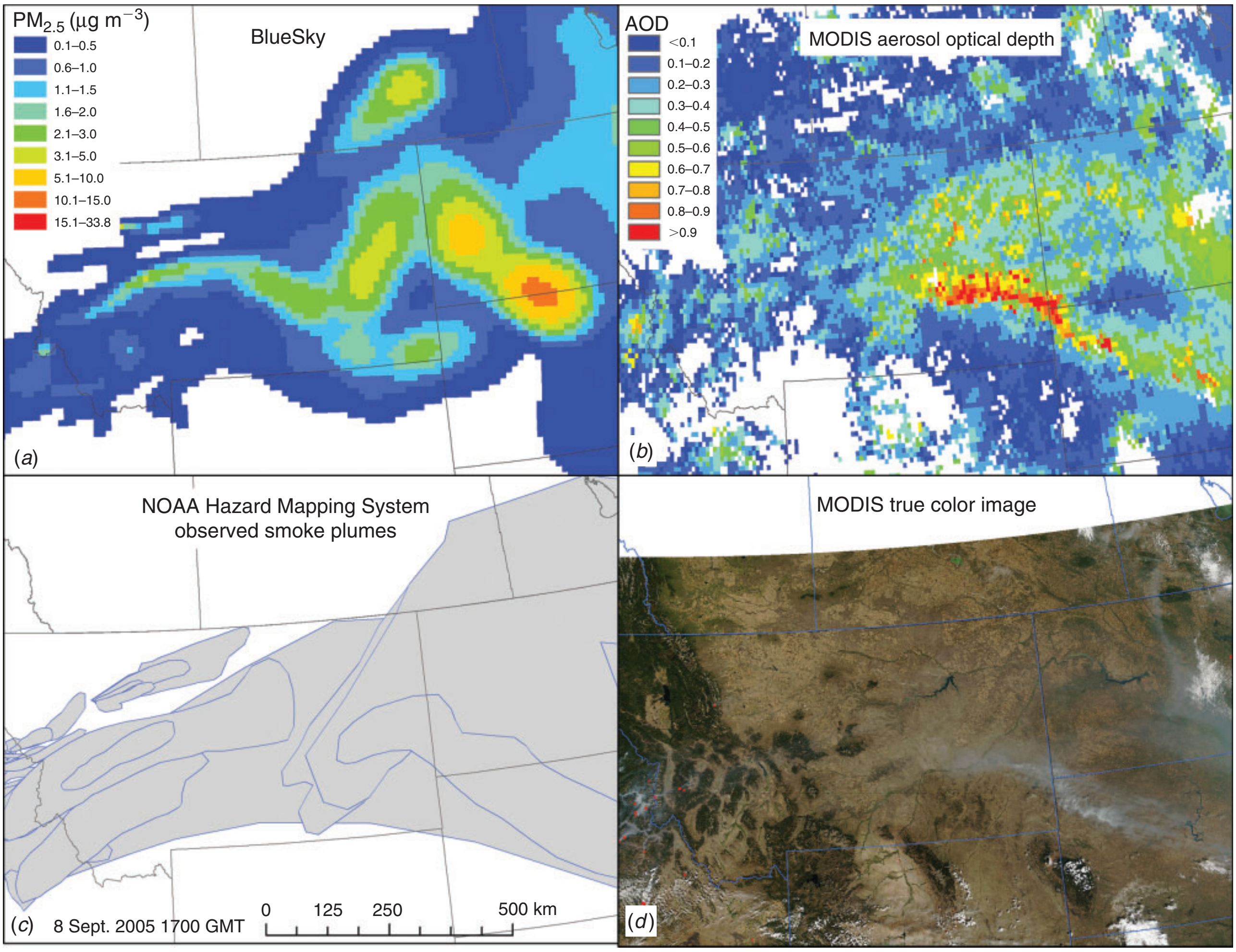

Fig. 6. BlueSky PM$_{2.5}$ surface concentrations compared with satellite derived observations for the Frank Church case study for 8 September 2005. The area shown is the region around Montana (see Fig. 5). (*a*) BlueSky ground concentrations. (*b*) MODIS satellite aerosol optical depth measurements (areas of white space indicate no data available). (*c*) Observed smoke plumes from the NOAA Hazard Mapping System. (*d*) MODIS true color image of the smoke plume (image courtesy of MODIS Rapid Response Project at NASA/Goddard Space Flight Center).

Dakota border. The modeled plume compares favorably with satellite observations (Fig. 6*b*, *c*, *d*). Although many fires were burning in the region, the Frank Church complex was one of the largest, and a distinct smoke plume is evident in the satellite images. The simulated PM$_{2.5}$ ground concentrations (Fig. 6*a*) show many of the same features as the NOAA Hazard Mapping System (HMS) smoke plume product (Fig. 6*c*), including the north–south spread. Areas of overlapped outlines indicate smoke plumes detected from various satellites used by HMS. The areas of highest modeled concentrations resemble the area of highest overlap. The Moderate Resolution Imaging Spectroradiometer (MODIS) satellite aerosol optical depth (AOD) measurement (Fig. 6*b*), an integrative measure of the entire air column's aerosol based on overall light attenuation, also shows good agreement with the modeled ground concentrations. The highest AOD measurements fall in the region of the largest modeled concentrations. Similarly, the MODIS visible imagery shows that the most visible smoke plume is similar in shape to the pattern produced by the BlueSky run. This result is typical of comparisons between BlueSky-enabled simulated surface concentrations and satellite observations for the Frank Church fire.

Inter-model variability

There are several sources of uncertainty in any calculation of smoke emissions or impacts. Two of these are the fuel loadings and the consumption calculations, and they tend to interact with each other. Fig. 7 compares the total consumption rates obtained when various combinations of fuel loading and consumption models are used (e.g. FCCS→EPM *v.* NFDRS→FEPS). To place these results on the same graph, the results are normalized by dividing by the total area burned, resulting in consumption per area burned. Not only does the choice of models change the total consumption considerably, but the results differ by fire location (Rex Creek *v.* Frank Church). This is because the fuel loadings are site-specific, and the consumption rates depend not only on the total fuel loading but also on the specific fuel loadings in each size class and on how the specific consumption model treats these internally.

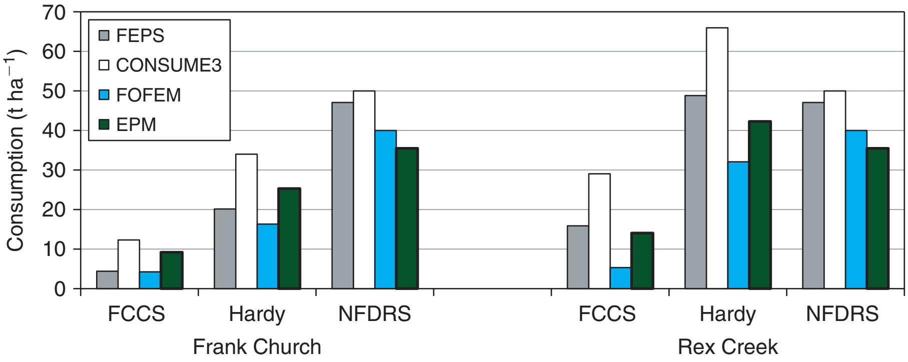

Fig. 7. Total consumption per hectare as calculated using the FCCS, Hardy, and NFDRS fuel loadings maps and the EPM, FEPS, FOFEM, and CONSUME3 consumption models for the Frank Church and Rex Creek case studies. These results are likely to be highly regionally dependent. See text for discussion and http://data.semip.org for further examples.

For these specific cases, the combination of fuel loading and consumption models can be seen to alter the output greatly, by more than a factor of 10. Variability across fuel loading models (while holding the consumption model constant) is generally greater than the variability across consumption models (while holding the fuel model constant), but in both cases the range varies substantially. Additionally, the specific models and model combinations with the highest consumption rates vary. In general, the Hardy and NFDRS fuel loadings here have higher consumption than FCCS, and CONSUME has the highest rate of consumption. These results are likely highly regionally specific, and more sites and fires need be examined to determine if these are actually systematic differences. To this end a follow-on study is under way (see *Summary* section).

Plume rise calculations – influence of fuel loading and consumption

Another source of uncertainty is the height of the simulated plume. The height of the simulated plume rise is important because this determines the vertical distribution of smoke emissions from the fire, which in turn affects the direction the smoke is carried. The vertical spread of smoke may encompass one or many atmospheric layers above the surface, which will typically have different transport directions. Near the surface, the smoke may be influenced and transported by terrain-dominated winds; if the smoke is pushed high enough, it can enter regional recirculation patterns such as the land–sea breeze, or if it is pushed through the mixing height, upper winds can transport the smoke large distances (Stein *et al.* 2009). If incorrectly simulated, the end-results may have misplaced plumes or low surface concentrations in the near-field.

Plume rise is calculated from the heat released with the fire in conjunction with the meteorological conditions above the fire, particularly the atmospheric stability. Because the heat released, along with other emissions (e.g. $PM_{2.5}$) are directly related to consumption, they are subject to the same variability and are therefore dependent on the specific choice of fuel loading and consumption model. Fig. 8 shows the effect of varying the fuel loading choice for the Rex Creek case. The difference in plume rise height is shown based on various choices of fuel loading model. The EPM consumption model is used throughout. The results show a net difference in plume rise that can be as much as 1000 m (Fig. 8). This difference is not constant, nor is it a constant ratio throughout the selected time period (14–30 August 2001), in part because the plume rise calculation is a non-linear combination of both the heat released and the meteorological conditions. The largest differences occur during the daily, active burning phase of the fire; during the quiescent periods, the plume rise differences tend to disappear.

Plume rise calculations – effect of multiple fire plumes

Plume rise is not well understood for wildland fire. Jain *et al.* (2007) investigated plume rise by using the buoyant line source and buoyant area source options in CALPUFF and comparing simulated results with aircraft- and ground-observed plume heights of burning wheat fields. The CALPUFF buoyant area source simulated plume rise closer to the aircraft observations of the plume tops, but neither the line nor the area source compared well with the ground observations. This spotlights the difficulty of not only simulating plume rise but quantifying plume rise. Furthermore, wildland fires act in complicated ways, with differential burning rates in different parts of the fire. The result is that the heat released by the fire does not always drive a single deep convective plume; instead, it may drive several different plumes of varying heights (Liu *et al.* 2006). To simulate this, the Rex Creek case was run for two additional scenarios: first, dividing the fire into five separate fires of 50, 25, 12.5, 6.25, and 6.25% of the original size respectively (the five-fire case), and second, dividing the fire into 10 separate fires of 10% of the original size each (the 10-fire case). In all three cases (one-fire, five-fire, ten-fire), the locations of all the fires were identical, and the total area burning at any one time was the same (Figs 9, 10). The difference is in the number of effective plumes used.

Maximum and average surface concentrations differed in horizontal coverage and value for the three cases for the period of 19–26 August 2001 (Fig. 9). This is the period when largest impacts were recorded at the town of Twisp, ~30 km north-east of the fire. The five-fire case shows substantially higher ground

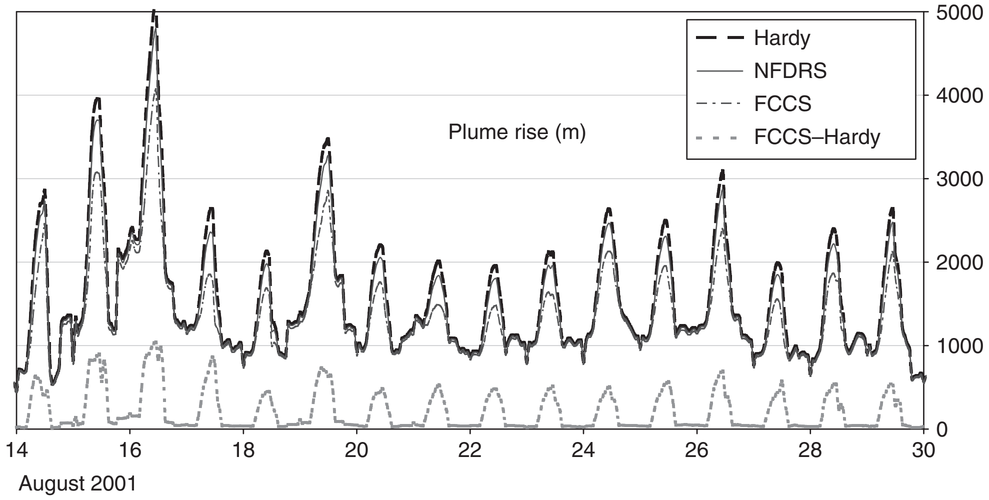

Fig. 8. Variation in the time evolution of plume rise for the Rex Creek fire based on fuel model used for the period 14–30 August 2001. Plume rise using the Hardy (dashed line), FCCS (dash-dot line), and NFDRS (solid light line) fuel loadings are shown as calculated using the EPM model. The difference between the Hardy and FCCS plume rise is also shown (light-grey dashed line).

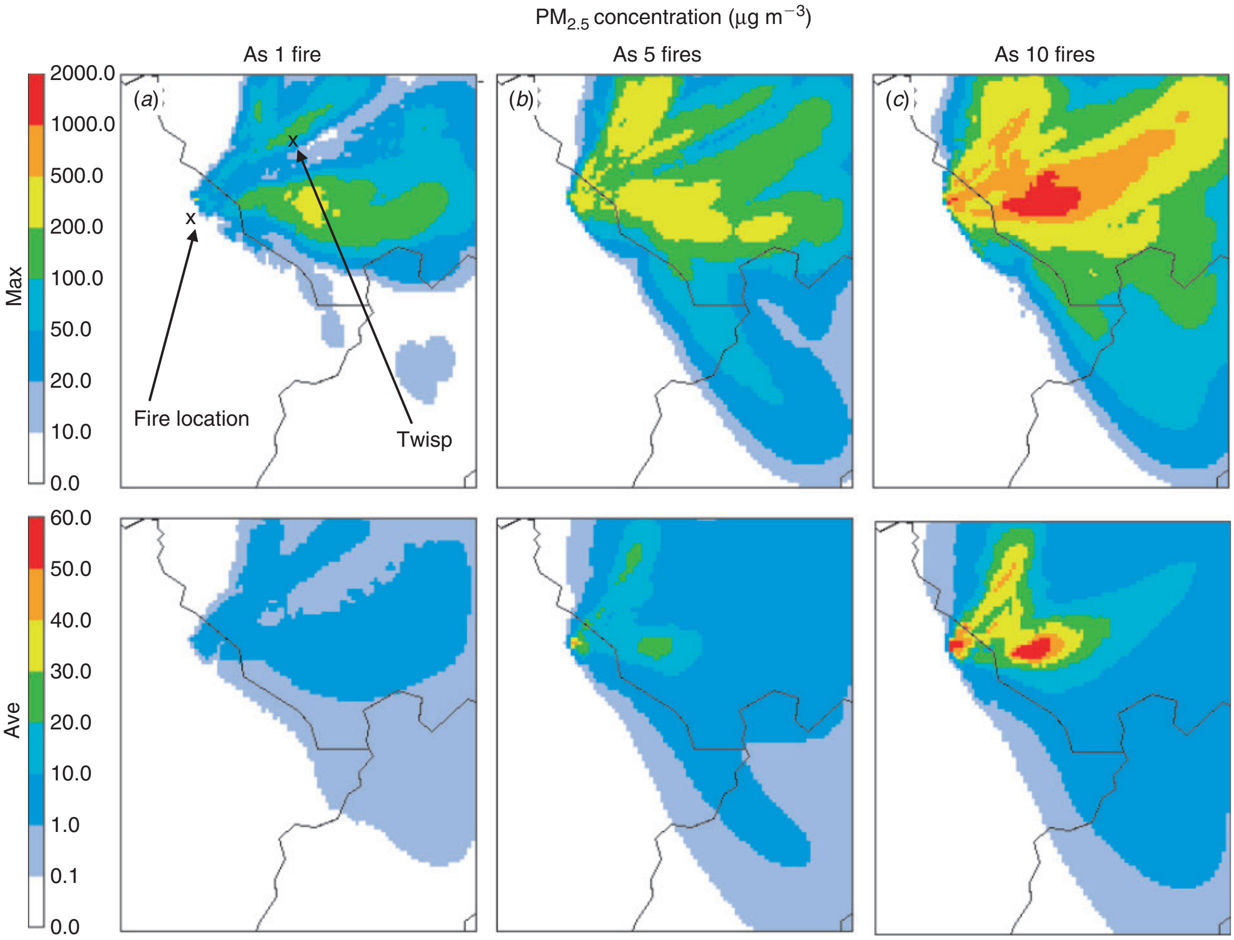

Fig. 9. Maximum hourly and average ground concentrations for the Rex Creek wildfire case study for the period of 19–26 August 2006 when the fire is: (*a*) treated as a single fire (one-fire case); (*b*) split into five fires with 50, 25, 12.5, 6.25, and 6.25% of the original area (five-fire case); (*c*) split into 10 equal fires of 10% the original area (10-fire case). In all cases the total area burned is the same. The locations of the fire and Twisp, WA, are indicated. See Fig. 5 for location map.

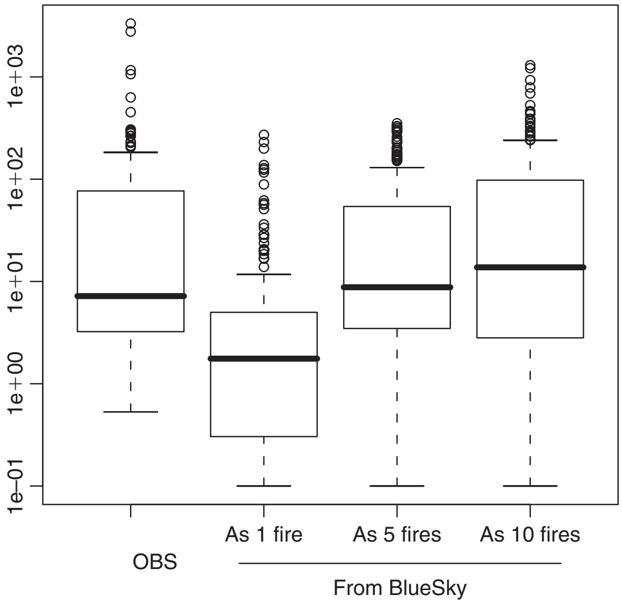

Fig. 10. $PM_{2.5}$ concentrations near Twisp, WA, for the Rex Creek fire for the period of 19–26 August 2001. Box-whisker plots showing observed concentrations (OBS) and BlueSky concentrations for the one-fire, five-fire and 10-fire cases (see text for details). Model concentrations are the maximum values along a 60° arc of constant radius (~40 km) from the fire centered on Twisp. Values below 0.1 are set to 0.1 for plotting purposes.

concentrations than the one-fire case, with the 10-fire case showing even higher concentrations. This is due to the lower effective plume rise, injecting the smoke into the atmosphere close to the ground, and resulting in increased near-field concentrations. This improves the overall model performance (Fig. 10).

$PM_{2.5}$ surface observations derived from light scattering (β_{scat}) measurements taken in Twisp, WA, are compared with the three fire core Rex Creek cases. Observation values are from a USFS Region 6 nephelometer placed in the town and calibrated to a federal reference method. Model values are derived by taking the maximum values along a 60° arc of equal distance from the fire (~40 km) centered on Twisp. Because of small errors in the model meteorology and topography, such an arc is more likely to be representative of the impacts at the town than the exact model grid cell. The number of fire cores changes the simulated dataset shape (Fig. 10). The one-fire case shows significantly lower $PM_{2.5}$ concentrations than those observed. The five-fire case has substantially better agreement, although it misses the very top-end values and shows too little variability. The ten-fire case improves the prediction of the very high-end values to some degree, but also causes the average value to become too high. These results suggest that basic knowledge of the fire behavior – such as spreading along a single unified front and forming a single smoke column, or spreading along many smaller fingers resulting in a more broken up smoke plume – can have a large impact on the model results.

Summary

The BlueSky smoke modeling framework has been developed to enable modeling of air quality impacts from fire. Using existing models in a modular framework, BlueSky integrates the state of knowledge of fuels, fire-activity reporting, emissions estimation, and smoke transport and chemistry. The component models available within BlueSky at each modeling step range from simple empirical calculations to more complex physical models, allowing for a wide range of implementation choices.

Designed originally to be a decision-support tool for prescribed burning activities, the sophistication, modularity, and distributed nature of the BlueSky system has allowed it to be successfully used by a varied user community: regulators, land managers, airshed coordinators and wildfire incident command teams, as well as the general public (O'Neill *et al.* 2005). BlueSky smoke predictions are now available throughout the contiguous US, and BlueSky smoke emissions are used in the Northwest AIRPACT-3 air quality prediction system (Chen *et al.* 2008*a*) and the US National Weather Service experimental smoke prediction product (Rolph *et al.* 2009). Other researchers have found utility in BlueSky's ability to compute emissions, and it is being used in a variety of research studies for emissions inventory work (e.g. Pouliot *et al.* 2005; McKenzie *et al.* 2006; Wiedinmyer *et al.* 2006; Chen *et al.* 2008*b*).

Modeled output enabled through BlueSky generally compares well with satellite plume observations (Fig. 6), with regard to overall plume shape and long-range transport. However, BlueSky tends to underpredict the near-field (<100-km distant) ground concentrations, as was seen in the Rex Creek case study (Fig. 10, one-fire case). Although significant variations exist between $PM_{2.5}$ emissions based on various model component choices (Fig. 7), these are insufficient to account for the model performance when compared with surface observations. It is apparent that choice of fuel loading and type influences emissions and plume rise (Figs 7, 8).

Knowing the available fuels for consumption through in-field measurements and analyses will help reduce uncertainty. Fuel loading is a large unknown in most fires, particularly with larger fires that burn through multiple fuel types over multiple model grid cells at different times. Additionally, none of the fuel loading components here captures variations within a single vegetation type, such as those caused by the presence or absence of built-up downed fuels. This is why onsite fuel estimates can be a critical component of fire activity data. However, even keeping the fuel loading constant, the consumption models exhibit significant (greater than a factor of 2) variation, and these ratios change depending on the underlying fuels distribution because of differences of how the various models treat different fuel types. Fuel loading heterogeneity and fuel consumption calculation accuracy remains an active area of research.

Treating the fire as having multiple fire cores and, therefore, multiple plumes seems to significantly improve model performance, at least as far as correcting the underprediction bias. The default in current fire smoke models is to treat the fire as a single large convective column (the one-fire case), while in actuality wildfires are often composed of several fires burning at the same time. Liu *et al.* (2006) found that splitting a fire into several component fires of various sizes results in substantial increases in near-field concentrations, similarly to results shown for Rex Creek (Fig. 9*b*, *c*) for the five-fire and ten-fire cases respectively. The five-fire and ten-fire cases showed dramatic increases in predictions of ground concentrations over the underpredicting one-fire case (Fig. 10), suggesting that knowledge of fire behavior is important to accurately simulate smoke impacts from fire.

BlueSky development, presently in β testing (Version 3.0), includes a complete rewrite of the framework code to improve modularity and ease of configuration and use. Notably, in Version 3.0, plume rise has been separated out into its own modeling step, allowing for more advanced plume rise models to be quickly developed and incorporated. Version 3.0 also enhances integration with SMARTFIRE, allowing for greater incorporation of satellite information for fire detections. Additionally, evaluation of the BlueSky system as a predictive tool is being carried out using *in situ* air quality monitoring networks, and work is under way to incorporate better fuel moisture calculations.

These enhancements have allowed BlueSky to be incorporated into new research initiatives. The upcoming Smoke and Emissions Modeling Intercomparison Project (SEMIP) is creating a structure for comprehensive examination of model-to-model variability in these areas as well as guidelines for model-to-observation evaluations. Additional work is also being done to make BlueSky a distributed web-based interactive tool that can be called by web applications and other models directly. The current version of the BlueSky code is available through the web (http://blueskyframework.org, accessed 2 October 2009).

These projects attest to the fact that the BlueSky smoke modeling framework provides a powerful tool that helps organize the state of knowledge of fuels, fire behavior, consumption, emissions, plume rise, dispersion and smoke. By integrating these multiple disciplines into a single framework, it provides a way to compare the state of knowledge in the various modeling steps, allowing researchers to advance the state of the science. By enabling smoke predictions and real-time forecasts that were previously unavailable, BlueSky provides land managers and air regulators a means to understand, discuss, and, where possible, mitigate the adverse effects of smoke.

Acknowledgements

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Appendix 1. List of models, acronyms, and websites

Cited information was available from listed websites on 2 October 2009

Acronym or model	Explanation
AIRPACT	AIRPACT-3 air quality forecast system: regional (US Pacific Northwest) system based using CMAQ http://lar.wsu.edu/airpact-3/
AOD	Aerosol Optical Depth: typically measured from satellite instruments such as MODIS
BlueSky	BlueSky smoke modeling framework: a framework that interconnects fuel loading, fire consumption, fire emissions, trajectory, dispersion, and air quality models http://blueskyframework.org
BURNUP	The consumption model implemented within FOFEM
CALMET	A meteorological preprocessor for the CALPUFF Gaussian puff dispersion model
CALPUFF	A Gaussian puff dispersion model developed under contract by Earth Tech Inc. for the US Environmental Protection Agency
ClearSky	ClearSky agricultural burning forecast system: regional (US, Washington and Idaho) system developed by Washington State University http://clearsky.wsu.edu
CMAQ	Community Multiscale Air Quality model: open-source full chemistry air quality model developed by the EPA http://www.cmaq-model.org/
CONSUME	CONSUME version 3.0 model: outputs fuel consumed and emissions by consumption phase http://www.fs.fed.us/pnw/fera/research/smoke/consume/index.shtml
CSV	Comma Separated Value format: a text-based data format that separates information with commas
EPA	US Environmental Protection Agency
EPM	Emissions Production Model Version 1.02: model of fire consumption and emissions (replaced by FEPS)
FCAMMS	Fire Consortia for the Advanced Modeling of Meteorology and Smoke: regional consortia run by the US Forest Service that produce experimental fire weather and smoke predictions http://fcamms.org
FCCS	US Fire Characteristic Classification System model: http://www.fs.fed.us/pnw/fera/fccs/
FEPS	Fire Emissions Production Simulator model: model of fire consumption and emissions (replaces EPM) http://www.fs.fed.us/pnw/fera/feps/
FOFEM	First Order Fire Effects Model: modeling system containing fire consumption and emissions components (BURNUP) http://www.fire.org/index.php?option=content&task=category&sectionid=2&id=12&Itemid=31
FASTRACS	Forest prescribed burn information system: for fires in Oregon and Washington State (US)
Hardy	Hardy *et al.* (1998) fuel loading map covering the US: as implemented in a fuel loading module in BlueSky
HYSPLIT	HYbrid Single-Particle Lagrangian Integrated Trajectory model: puff/particle model that produces trajectories and concentrations http://www.arl.noaa.gov/ready.html
ICS-209	Incident Command System 209 reports: US wildfire reports filed by ground teams
MM5	Mesoscale Meteorological model Version 5: widespread community model; predecessor to the WRF model http://www.mmm.ucar.edu/mm5/
LINUX	LINUX operating system: variant of the UNIX operating system
MODIS	MOderate Resolution Imaging Spectroradiometer: instrument aboard polar orbiting Terra and Aqua NASA satellites
NAAQS	US National Ambient Air Quality Standards
NASA	US National Aeronautics and Space Administration
NCAR	US National Center for Atmospheric Research
NetCDF	Network Common Data Format: open-source binary computer data format maintained by Unidata
NFDRS	US National Fire Danger Rating System: the official US system for evaluating fire danger; also includes fuel loading information and other codes
NMHCs	Non-methane hydrocarbons
NOAA	US National Oceanic and Atmospheric Administration
NWRMC	Northwest Regional Modeling Consortium: a regional modeling consortium located in the US Pacific Northwest; used as a model for the FCAMMS http://www.atmos.washington.edu/mm5rt/
NWS	US National Weather Service: official, operational weather and air quality forecasts http://weather.gov/aq
ODF	Oregon Department of Forestry
PERL	Practical Extraction and Report Language: a computer programming language
PM	Particulate matter (aerosol particulates): $PM_{2.5}$ and PM_{10} refer to particulates less than 2.5 and 10 μm respectively
RAZU	Prescribed burn information system: for fires in the US states of Montana and Idaho
SMARTFIRE	Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation fire information system: reconciled satellite and ground report system for fire information http://getBlueSky.org
SMOKE	Sparse Matrix Operator Kernel Emissions model: component model used for conditioning emissions for CMAQ
SMOKEM2	Prescribed burn reporting system: run by the Washington State (US) Department of Natural Resources
STI	Sonoma Technology, Inc.
USFS	US Forest Service
UNIX	UNIX operating system
WRAP	Western Regional Air Partnership: consortium of 13 western US states
WRF	Weather Research and Forecasting meteorological model: successor to the MM5 meteorological model http://wrf-model.org