6.7   AUTOMATED, REAL-TIME PREDICTIONS OF CUMULATIVE SMOKE IMPACTS FROM PRESCRIBED FOREST AND AGRICULTURAL FIRES

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1.0 INTRODUCTION

Smoke management is becoming increasingly complex as the use of fire to preserve or maintain forest health and reduce hazardous fuels is increasing and as smoke from forest and rangeland burning is combining with smoke from traditional agricultural fires to compete for airshed space. The cumulative smoke impacts cross state and federal boundaries, affecting regional haze, visibility, human health and other air-quality related values.   The cumulative impacts are making land management and air regulation increasingly complex.

In addition to cumulative smoke impact, implementation of the Clean Air Act and new Regional Haze Rule are prompting regulatory agencies to require that land managers become more active in smoke modeling and real-time emission tracking. Also, implementing the National Fire Policy and Cohesive Strategy requires improved understanding of smoke impacts that can limit the use of fire.

Accurate**,** real-time, automated prediction of emissions and impacts are needed. During the 2000 fire season thousands of people were affected by high smoke concentrations for long periods of time, but citizens tolerate very little smoke from prescribed burning. How can we more effectively inform and warn of impending impacts from smoke? Will smoke impacts from the wildfires affect people's acceptance of an aggressive prescribed fire program? How can we use fire to manage ecosystems across the landscape without filling the airshed with smoke, violating National Ambient Air Quality Standards (NAAQS), imposing health hazards, degrading visibility, or creating a public nuisance?   How much smoke contributes to regional haze?

Although smoke dispersion models have been available for a number of years, they either are too complicated to be run operationally or too simple to be realistic. In addition, few land management agencies have the required skills to effectively run and analyze

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models. Therefore, their use has been of limited value in the day-to-day management of smoke and tools that do exist are under-utilized or inappropriately linked. As a result, they are poorly validated and hold limited trust among our regulatory partners, planners, and managers.

2.0 "COMMUNITY" MODELING SCHEME

The northwestern United States provides a unique environment for developing and assessing a system for predicting cumulative effects of biomass smoke and tracking emissions. It has a long history of interagency collaboration in air quality and mesoscale modeling, several components required for an integrated modeling framework already are operational in the northwest (e.g., MM5 and FASTRACS), and there is an active group of users who are familiar with smoke models.

Because of our positive experience with the multi-agency support of real-time mesoscale weather modeling with MM5 in the northwestern U.S. (Ferguson 2001), we embarked on a similar "community" development and application approach for modeling smoke.   The inter-agency, cooperative environment ensures that concerns from air regulators, smoke managers, and fire operations and planning groups are included in the development process and that sufficient applications meet the needs of all cooperators. We coined the project "BlueSky."

While the BlueSky modeling framework should have application anywhere, we chose to develop a working prototype in the northwestern United States (BlueSky-Northwest) where several necessary components already are working and readily available.

The BlueSky-Northwest Smoke Modeling Committee includes many members of the MM5 Northwest Regional Modeling Consortium. Additional members include potential local users to help refine output products and national representatives to ensure wide application in other regions of the country. Below is a list of agencies currently involved on the committee. We hope to include representatives from the Bureau of Land Management, National Park Service, Fish and Wildlife Service, and county and tribal governments.

Bureau of Land Management
Environmental Protection Agency
Idaho Department of Environmental Quality
Montana Department of Ecology
Northwest MM5 Regional Modeling Consortium
Oregon Department of Forestry
Oregon Department of Environmental Quality
Pacific Northwest National Laboratory (Battelle)
USDA-FS, Region 1 Air
USDA-FS, Region 4 Air
USDA-FS, Region 6 Air
USDA-FS, Region 6 IMS
USDA-FS, Region 6 Fire
USDA-FS, Pacific Northwest Research Station
USDA-FS, Rocky Mountain Research Station
USDA-FS, Washington Office Air Program
University of Washington
Washington Department of Natural Resources
Washington Department of Ecology
Washington State University

We have divided the committee into a development group, which includes mostly technical modelers (led by the USDA-FS Pacific Northwest Research Station), a marketing group (led by the USDA-FS Region 6 Air Program) to help ensure applicability of products being developed, and an evaluation team (co-led by the USDA-FS Regions 1 and 6 Air Programs). Additionally, we are working closely with similar regional modeling consortia in other parts of the country to help implement the smoke modeling framework in real-time projects across the United States.

3.0 MODELING FRAMEWORK

The BlueSky-Northwest project takes advantage of a long history of real-time mesoscale meteorological modeling in the northwestern United States (Ferguson 1998, 2000, and 2001). The real-time mesoscale meteorological pre-dictions have afforded a unique opportunity to rapidly and continuously view, evaluate, and improve model predictions. Attributes of local and regional meteorology are more easily identified when model output can be instantly compared to current conditions. A trust in MM5 model output has been achieved by involving users in the development and evaluation process. We believe that a similar framework for viewing smoke model output will increase our ability to evaluate and potentially improve smoke modeling techniques for the variety of applications across regulatory, management, and user agencies. To meet this end, we are developing an automated, real-time, web-based smoke modeling system framework.

The functioning system eliminates the burden on users for copious inputs, provides immediate feedback on accuracy, shows cumulative effects of smoke from prescribed agriculture and forest burning across land ownerships, and creates an efficient emission tracking system. In addition, the system offers a framework for developing and testing model components that include

fuel condition, fuel structure, fire spread, consumption, and emissions. All of these components need to be modified and improved for real-time, automated application.

Basic elements of the smoke modeling framework include:

- Source Characteristics
- Emissions
- Weather
- Smoke Dispersion
- Background Air Quality
- Output Products
- Verification

3.1 Source Characteristics

Providing real-time source characteristics may be the most difficult task of BlueSky. To drive emission and smoke dispersion models, the mass, structure, and condition of available fuel must be known. Also required are the time, duration, and style of ignition. There are a number of ways of acquiring these data, which include plan and accomplishment reporting systems, use of remote sensing data, and methods of modeling or estimating needed parameters.

While most agencies keep track of biomass emissions through an annual reporting system, few have the ability to track burning activity on a daily basis. Also, because each state and tribe has its own implementation plan for meeting national air quality standards, it is difficult to find consistent data of the quality and quantity needed for real-time smoke dispersion and emission tracking. This makes it difficult to use reports for obtaining source characteristics.

Because there is insufficient reporting of planned and accomplished burns, remote sensing may offer input alternatives for source characterization needed in BlueSky. Advances in remote sensing have allowed the detection of dynamic wildfires, however, much of the burn activity in prescribed fires is either too small or too cool (detection algorithms use temperature differences to identify fire perimeters) to be detected by current satellite technology. Also, most high resolution imaging equipment currently resides on polar orbiting satellites, whose over-flights may be as infrequent as once per week and not less than twice per day. Therefore, the timing and technology of satellite detection restrict its use in real-time applications.

For BlueSky we also are looking into satellite-derived fuel structure and fuel condition. Products are being developed that use satellite-derived vegetation and other attributes to estimate the mass, structure, and distribution of fuel. Also, radar technologies are being adapted to detect fuel moisture. Unfortunately, the products are not yet available at the spatial and temporal resolutions required for real-time modeling.

In many situations, it is possible to estimate mass and structure of fuels and, to some extent, the ignition pattern just by knowing the reason for burning and the general vegetation class. For example, an under-story burn in a pine forest to reduce fine fuels

generally has a relatively light fuel load and is ignited by hand in a few hours or more. On the other hand, burning harvest residue in a fir forest typically includes heavy fuel loads and short ignition periods. Emissions and resulting smoke dispersion can be estimated by defining typical characteristics in different classes of burn styles (Ferguson et al. 1998).

Despite the deficiencies of reporting, the Northwest benefits by having one of the most sophisticated reporting systems in the country. Several years ago the States of Washington and Oregon teamed with the USDA-Forest Service (FS) and USDI-Bureau of Land Management (BLM) to build a Fuel Analysis, Smoke Tracking, and Report Access Computer System (FASTRACS: <http://www.fs.fed.us/r6/fire/fastracs/>). Each BLM and FS district now submits burn plans and accomplishments to a centralized database that is updated with every new entry. All the data needed to drive smoke dispersion models and calculate emissions are in FASTRACS and available in real-time (daily). Unfortunately, only federal agencies in Washington and Oregon, which include about 50% of acres burned in the region, currently use FASTRACS.   Other burners employ simpler daily or annual reporting systems. The BlueSky-Northwest modeling committee, however, is working with all states in the Northwest MM5 modeling domain (Washington, Oregon, Idaho, and Montana) to help facilitate appropriate reporting systems.   For example, the state of Washington has begun developing a new automated agricultural reporting system much like FASTRACS that we hope will be adopted by other states.   Also, we are communicating with state and federal land managers in other regions to help explain the reporting requirements for a smoke modeling system.

We are using historical data available in FASTRACS to determine the range of source conditions we might expect. For example, Figure 1 shows total acres burned in about a one-year period from the different types of burning activities in Washington and Oregon. Differences in amount treated for each type class may be due to the different patterns of land ownership in each state. About half of public lands in Washington are managed by the state whereas large portions of public land in Oregon are managed by the BLM.

The elements of source characteristics required at least a day before a planned burn include:

- Location of fire
- Fuel load by size class
- Fire type (an indication of fuel structure)
- Fire size
- Ignition time
- Ignition pattern

All of these data for prescribed fires currently are in FASTRACS. We estimate fuel mass, structure, and condition, and the time and pattern of ignition from fires not included in FASTRACS (i.e., other than FS or BLM) by whatever data currently are available from states.

Acquiring source characteristic information for wildfires is more complex and discussed in section 4.0 below.

At the time of ignition we also need to know the moisture content of 10-hour and 1000-hour fuels averaged over the burn area. Currently MM5 is being linked to the National Fire Danger Rating System, which includes fuel moisture elements.   This will give predictions of fuel moisture at 4-km and 12-km spatial resolutions.   Finer scale information is needed, however. Therefore, we are developing a scheme that will incorporate the 1-km spatially distributed fuel moisture observations that are available from the Wildland Fire Assessment System (WFAS: <http://www.fs.fed.us/land/wfas/>) and experimenting with a terrain algorithm that will approximate unit-scale moisture based on slope and aspect.

3.2 Emissions

There are two methods currently available for estimating emissions from wildland fire.   Both are models of fuel consumption based on theoretical combustion equations with empirically-derived coefficients. Emissions are derived from look-up tables of standard emission factors (AP-42 US Environmental Protection Agency 2000), which include most carbon gases and several particle-size classes.

The CONSUME model (Ottmar et al 1993) estimates total emissions and emissions in the flaming and smoldering stages by treating the burn area as a relatively homogenous distribution of fuel elements. BurnUp (Albini et al 1995; Albini and Reinhardt 1995 and 1997) estimates total emissions by consider-ing each fuel element separately and its position relative to other burning elements. The two methods yield similar results.

Emission rate is determined separately.   In BurnUp, rates of smoldering and flaming are approximated with best-known values (Reinhardt, *personal communication* 2000). CONSUME is coupled with an Emission Production Model (EPM: Sandberg and Peterson 1984) that derives emission rate from
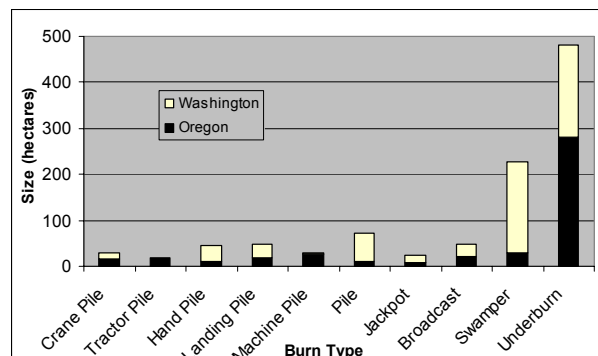

Figure 1. Total area treated with prescribed wildland fire for different types of burns in Washington and Oregon as reported in FASTRACS during the past year.

theoretical equations with empirical coefficients of flaming rate and smoldering rate (Sandberg and Peterson 1984; Ferguson and Hardy 1992).

BurnUp recently was coupled to a fire-spread model, FARSITE (Finney *personal communication* 1999). This allows emission rate to be coordinated with spread rate. We are experimenting with the use of BurnUp/FARSITE for the wildfire case study as explained in section 4.0 below.

EPM, as coupled with CONSUME, already is linked to several smoke dispersion models (Breyfogle and Ferguson 1996) and to FASTRACS. Also, it provides a reasonable approximation of emission rates (Figure 2). Therefore, it is a logical choice for inclusion into the prototype BlueSky-Northwest modeling framework.
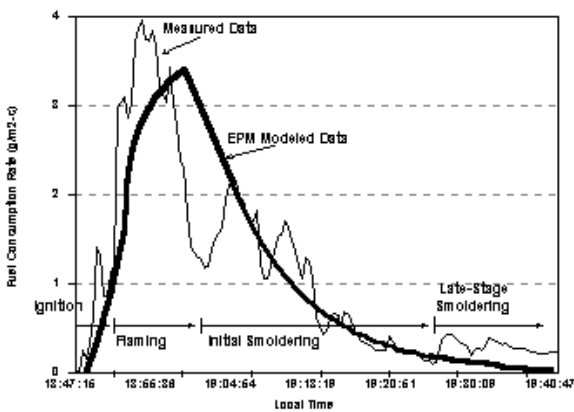

Figure 2. Consumption rate modeled by EPM (heavy line) and measured (light line) with tower-mounted samplers over a prescribed wildland fire.

agency, state, and national boundaries. Use of 12-km domain affords predictions out to 60 hours in advance.

Even though MM5 can simulate many of the blocking patterns that are common in mountainous terrain (Steenburg et al 1991), because it is a flow model using terrain-following sigma coordinates, some accuracy may be lost when simulating the trajectories of airborne particles. The diagnostic model, CalMet (Scire and Robe 1997) and other models like it, explicitly derive the conservation of mass around blocking terrain and is designed as an interface between available meteorology and smoke dispersion models.   Currently the awkward linkage between MM5 and CalMet is being modified.

While the 38 sigma levels in the MM5 real-time simulations are sufficient to resolve most vertical patterns of smoke dispersion, the 12 km horizontal resolution may be too coarse to capture the finer details of lateral dispersion, especially at night when smoke tends to follow small variations in the underlying terrain. We have an option of downscaling the MM5 meteorology to about 1 km[1] with a diagnostic

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[1] Finer resolutions are possible but depend on available

meteorological model such as CalMet.   We are embarking on an analysis of scale with the wildfire case study (section 4.0 below) to determine an optimal resolution for real-time simulation of cumulative smoke impacts.

3.4 Smoke Dispersion

There are many ways of modeling the dispersion of smoke.   These include Lagrangian models (particle, Gaussian puff, Gaussian plume) and Eulerian models (box, grid, photochemical). Most Lagrangian dispersion
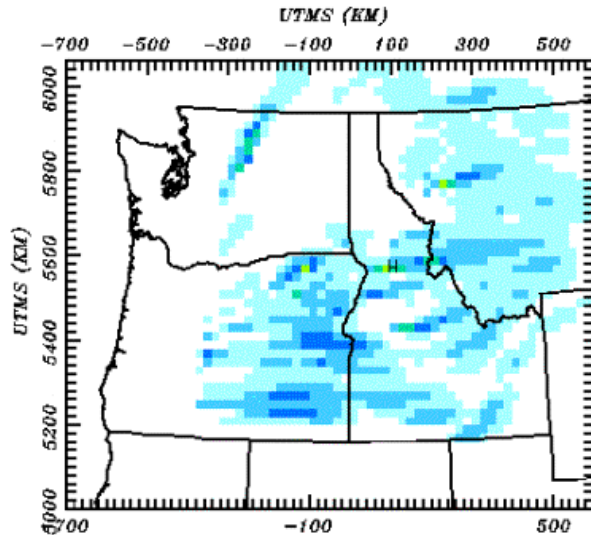

Figure 3. Surface concentrations of particulate matter that is less than 10 microns as simulated by CalPuff at 80-km resolution with idealized extreme prescribed fire emissions.

models were designed for use with industrial stacks and assume a simple plume-rise and constant rate of emissions. Eulerian models cannot predict the timing and location of plume impact with sufficient accuracy for smoke managers.

For the BlueSky-Northwest project we chose to followed a preliminary evaluation of smoke models (Breyfogle and Ferguson 1996) and recommendations from the interagency working groups (Express Team and TASET) to employ a Gaussian puff model. One such model, CalPuff (Scire et al 1995) already is linked to the MM5 meteorological model and the EPM variable emission rate model, and can simulate cumulative impact from multiple fires. Also, CalPuff is being evaluated as a regulatory model by the Environmental Protection Agency.

An example of cumulative surface concentrations from an extreme prescribe fire case as simulated by CalPuff at 80-km resolution is shown in Figure 3.   A CalPuff simulation of the cumulative impacts from a range fire, an agricultural fire, and a

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terrain and land-use data.

prescribed forest fire at 1-km resolution is shown in Figure 4a.   Figure 4b shows predicted surface concentrations for several species at point C in Figure 4a.
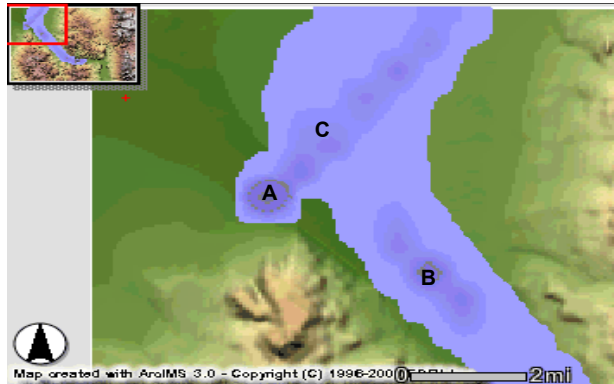

Figure 4a.   Calpuff simulation of surface concentrations accumulated from an agricultural fire (A), a range fire (B), and a forest fire (source region at head of valley not shown in zoom).
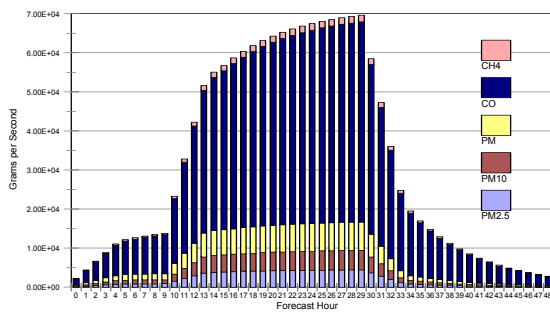

Figure 4b.   Calpuff predicted hourly surface concentrations of CH4, CO, PM, PM10, and PM2.5 in smoke accumulated at point labeled C.

3.5 Background Air Quality

Atmospheric concentrations of particles and gases from automobile exhaust and industrial stacks in the Puget Sound region of the Northwest are being determined in real-time by an Eulerian-grid photochemical model, CalGrid, by other members of the Northwest Regional Modeling Consortium.   CalGrid soon will be replaced with CMAQ, a component of Models3, and the domain will be expanded to include the Columbia Basin airshed (MM5's 12-km domain). The CalGrid, or CMAQ, simulations represent "background" concentrations, which compete with biomass smoke for airshed space.   The coincident simulations of "background" concentrations with biomass smoke trajectories will afford another layer of cumulative impact analysis.   Also, because the "background" work is being conducted within the Northwest community of modelers, regulators, and users, we hope to tie the output from BlueSky-

Northwest with CalGrid and CMAQ to understand the contribution of biomass smoke to regional haze.

3.6 Output Products

The BlueSky-Northwest modeling framework is running on a 40-node "Beowulf" PC cluster at the USDA-Forest Service, Seattle Forestry Sciences Laboratory (SFSL).   This allows complete and rapid automation with very little impact on users. It has the capability to use any state-of-the-art component for determining weather, fuel load, fuel consumption, emissions, and dispersion.   It is run nightly for both planned and accomplished burns, with output from 12 to 60-hour predictions available before 5am local time each day.

Output is available through ArcIMS, an Internet-mapping software that allows users to interrogate the mapped data. We are coordinating the web-hosted products with the EPA who have developed a "one-environment" information server called RAINS. A subset of RAINS is called B-RAINS or BlueSky-RAINS. On this site we are creating information that will help inform about potential impacts, plan emission contributions, manage smoke and other emission sources, and perhaps mitigate potential harmful impacts.   The B-RAINS products include output from the BluSky smoke modeling framework, the CalGrid or CMAQ "background" simulations, attributes from MM5 and other weather sources that assist smoke managers, such as ventilation index, trajectory winds, and boundary-layer height, methods of calculating forward and backward trajectories to and from sensitive receptors, and real-time emission-tracking tools.

Each night the most current FASTRACS file is imported to the SFSL PC cluster through ftp. Planned burns for the next 2 days and accomplished burns for the current day are extracted.   The extracted FASTRACS data are used to generate total emissions and emission rates.   The emission totals are ported to B-RAINS, where they are displayed in a format similar to the example shown in Figure 5.

In addition to importing FASTRACS data, MM5 grid fields from its 0Z initialization are ported to the SFSL PC cluster through the university high-speed network.   Emission rate data (calculated from FASTRACS information) and MM5 weather data are inputs to CalMet/CalPuff. Smoke dispersion from all accomplished fires for the current day is run separately, saved for verification (section 3.7 below), and accumulated with the next two days of planned ignitions when holdover smoke exists.

Maps of PM2.5 surface concentrations are generated for each hour of the 12 to 60 hour prediction period and configured into ArcIMS (Figure 4a). Through ArcIMS, users can drill into the data to observe hourly concentrations of all predicted species (Figure 4b).
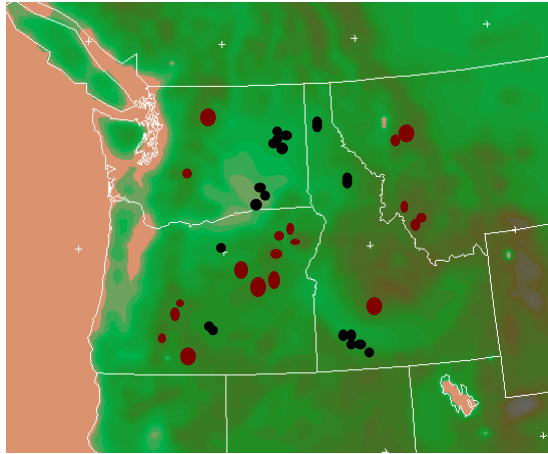
Figure 5. Example map showing emissions from accomplished burns in the BlueSky-Northwest modeling domain for one day. Colors of dots represent burn type. Size of dots represent emission totals.

3.7 Verification

Continuous generation of real-time smoke-impact predictions is expected to help understand the value of smoke models for management, permitting, and monitoring and to help define ways in which modeling components can be improved. To accomplish such evaluation, significant effort is underway to verify the BlueSky-Northwest model output against observations. Partners in each state are cataloguing all available surface observations, which are transmitted to the SFSL computer, where they will be compared to model output for real-time verification. The observation data also will be ported to the B-RAINS web server, where they will be available for monitoring. Early verification will be from the readily available observations of surface particle concentrations. As data on visual range from IMPROVE sites and optical depth from satellites become more available we plan to integrate them into the real-time verification procedures.

In addition to the continuous verification statistics, we are gathering data to perform model verification on selected case studies. These include the 2000 wildfire season, described in section 4.0 below, and several prescribed fires in the region. The case study experiments are being coordinated with local partners and scientists at the USDA-FS Rocky Mountain Research Station.

We hope that by making smoke predictions available in real-time, smoke and fire managers will have the opportunity to experience smoke impacts at the same time they are being modeled. The large number of users on the BlueSky smoke modeling committee will offer critical feedback on how the model is functioning during the wide range of applications.

4.0   WILDFIRE CASE STUDY

The 2000 wildfire season in the northwest produced an exceptional amount of smoke from a number of fires. The event began in late July, became critical in August,

and remained a concern through early September. Local, state, and federal agencies in the area collaborated to document smoke impacts. In addition, the Bureau of Land Management and USDA-FS in Idaho and Montana, and SFSL have collaborated to acquire all available meteorological observations.

While the event lasted over 8 weeks, a very critical period centered over the Bitterroot Valley, south of Missoula, Montana, lasted about 10 days in early August. We have created a nested modeling domain (Figure 6) centered over the Northern Rockies at 36-km horizontal resolution and 12-km, both of which will run for the entire 8-week period. An inner nest of 4-km will be centered over the Bitterroot Valley, which will run during the most active fire period in early August. From each domain, the CalMet diagnostic wind model will be used to downscale MM5 products to 1km.   The 36-km scale is similar to regional climate models and many synoptic meteorological models. The 12-km scale is the operating resolution for BlueSky-Northwest. To resolve many of the terrain features that influence smoke trajectories, 1 to 4 km are needed. Having 4 differently scaled domains will allow a detailed analysis of the effects of scale on modeling the transport and dispersion of smoke.
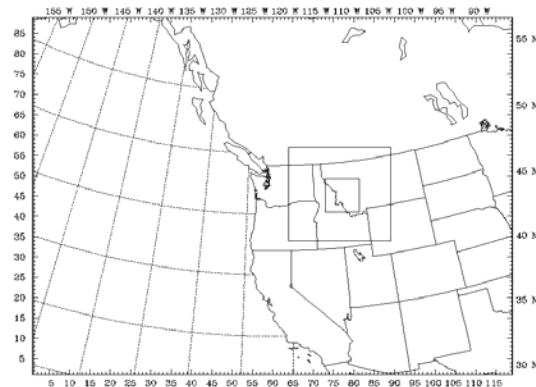

Figure 6. Modeling domain of the BlueSky 2000 wildfire season case study. The three nests include a 36-km outer domain, a 12 km 2nd domain, and a 4 km 3rd domain, centered over the Bitterroot valley.

Defining source characteristics of wildfires is even more difficult than for pre-planned prescribed fires. Ignition patterns are related to fire spread rates, which are difficult to predict, and wildfires migrate through complex fuel load and fuel condition patterns, making it difficult to accurately define those values. A major reason for conducting the case study is to develop a method of incorporating source characteristics from wildfires into the BlueSky automated framework for smoke prediction.

Because we do not know the level of accuracy needed at the source to produce reasonable simulations

of smoke impact at receptors, we are planning to test two methods of defining source characteristics. Each method will be tested on 2 fires that were isolated from the main smoke events and for which there were nearby observations of particle concentrations. Each method will use the same meteorological inputs and the same pre-burn fuel load and fuel condition approximations.

The first source characterization method uses the tools in the prototype of BlueSky-Northwest, which include CONSUME/EPM. To do this, fire spread rate (or ignition pattern) is highly parameterized. Available observations of fire perimeters are partitioned into 6-hourly periods with fire spread assumed to be least in the nighttime periods and most in the daytime periods. We expect this method to be rapid, which is a benefit in modeling the numerous large fires in the case study.

The second source characterization method will test the newly coupled models of FARSITE/BurnUp (Mark Finney *personal communication* 2000). Because FARSITE predicts burn perimeter, daily perimeter observations will only be used to nudge FARSITE's perimeter calculations, where spread rate and resulting emissions from BurnUp are modeled directly. Currently, FARSITE is computationally expensive, especially in the coupled mode with BurnUp. The initial test fires will help us evaluate whether too much accuracy is lost when parameterizing spread rate for CONSUME/EPM emissions or if the computational expense of FARSITE/BurnUp adds sufficient accuracy to warrant its application.

Daily observations of fire perimeters and the remote sensing of fire activity is made difficult by obscuring smoke, complex terrain, and the patchiness of consumption. Reports were logged each day only for fires exceeding 100 acres, which means that smoke from many small fires is not considered. Also, satellite-derived perimeters may misinterpret cool or small fires and there are problems geo-referencing satellite images. Therefore, there are large errors expected in defining source characteristics. Through the case study, we hope to determine if the inherent errors are within an acceptable range for reasonable smoke simulations.

The CalPuff smoke dispersion model will be run as it is configured for BlueSky-Northwest on the 12-km domain for the entire 8-week period, with smoke from one day contributing to smoke generated on subsequent days. CalPuff also will be run for shorter periods on the 4-km and 1-km domains.

Verification will use the available surface observations of hourly particle concentrations (PM2.5 and PM10). In addition, if available, we will test the model against optical depths determined from satellite observations. Through this effort, we hope to develop guidelines for monitoring and assessing emissions from wildfires.

5.0   CONCLUSION

The BlueSky smoke-modeling framework is designed to produce real-time predictions of cumulative smoke impacts. The automated, continuous, real-time verification of model output will allow us to better evaluate the value of smoke modeling and determine where improvements are needed to help make smoke-model tools more applicable to user needs. Valuable by-products of this effort include:

- real-time emission tracking,
- an automated smoke-observation monitoring system, and
- maps of planned and accomplished prescribed fires, which can be used to help allocate resources.

Thus far we have completed documentation of smoke impacts from the 2000 fire season in Montana and Idaho and development of the MM5 fields needed for the wildfire case study. We have created or refined links between all the required modeling components, established procedures for gathering input files, and completed some preliminary tests of the prototype framework. Initial steps to automate the smoke observation database have been taken and a prototype of the web site is complete.

The BlueSky smoke modeling framework is an ambitious project. While we hope that the framework will show effective use of smoke models for many management needs, the automated, real-time application will provide truthful knowledge about the valid use of such models for prescribed fire and wildfire applications. We may very well find that available inputs are too coarse for the type of modeling results users require. If this is the case, BlueSky may open the door for a brand new approach to smoke management.

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