Southern Smoke Simulation System - a framework for modeling smoke impacts from prescribed burning in the South

Scott Goodrick, Gary Achtemeier and Yongqiang Liu
USDA Forest Service, 320 Green St. Athens, GA. 30602

ABSTRACT

Fire is a natural disturbance in many ecosystems, although one that can have adverse impacts, particularly to nearby communities. Prescribed fire is an important tool for land managers as its judicious use can allow fire back into ecosystems to perform its essential role in maintaining ecosystem health and function while minimizing adverse impacts on the local community. Smoke is the prime adverse impact from prescribed burning. Land managers need tools that better help them estimate the impact of their smoke on air quality and public safety. The Southern Smoke Simulation System (4S) is being developed to assist land owners in managing smoke by integrating a series of computer models with database and GIS technologies. For regional smoke issues, 4S brings prescribed burn information into the CMAQ regional air quality model for addressing issues such as regional haze. On a more local scale, 4S makes use of the BlueSky framework, developed by the Pacific Northwest Research Station of the U.S. Forest Service to address potential visibility issues on roadways and possible health impacts due to high concentrations of particulate matter. At even smaller scales, 4S implements local smoke models design to simulate the movement of smoke at night, a severe roadway hazard. Through 4S, the user is presented with a consistent tool for evaluating smoke impacts at multiple scales.

INTRODUCTION

The southeastern United States is one of the most productive forested areas in the country, comprising 40% of the Nation's forests, approximately 200 million acres (81 million ha) (SRFRR, 1996). A favorable climate leads to rapid growth within these forests and hence a rapid buildup of fuel that supports a rapid fire return interval of 3-5 years (Stanturf et al., 2002). Prescribed fire is a forest management tool designed to mimic the beneficial role of fire as a mechanism for ecosystem disturbance while minimizing the potential adverse impacts associated with a wildfire. One adverse impact of wildland fires, whether prescribed fire or wildfire, is smoke. Smoke presents hazards to public health and safety. Smoke from wildland fires is major sources of particulate matter (both PM 2.5 and PM 10), NO_2 and volatile organic compounds (VOCs) which can act to increase O_3 concentrations. Particulate matter, especially PM 2.5 is a risk to both human health and the environment as these small particles are able to penetrate deep into the lungs and are major cause of visibility impairment that can lead to smoke related highway accidents. In the southeastern United States prescribed fire is used to treat 6-8 million acres (2-3 million ha) of forest and agricultural lands each year (Wade et al., 2000).

In 1998, the Environmental Protection Agency (EPA) issued the Interim Air Quality Policy on Wildland and Prescribed Fire to protect public health and welfare by taking steps toward mitigating the air quality problems associated with smoke. As part of this policy the EPA urged states to develop and implement some form of smoke management program (SMP). The goals of an SMP are to mitigate the nuisance and public safety hazards (to roads and airports) posed by smoke from wildland fires and to prevent the deterioration of air quality (violations of the National Ambient Air Quality Standards – NAAQS and visibility reduction in Class I Federal areas). While land managers had become accustomed to implementing smoke management practices to minimize the threat of local smoke hazards and nuisance, taking a more regional view of smoke management to address air quality issues is a major departure from previous practices and requires the development of new tools. New tools are also required by the air quality community as wildland fire had previously been largely under the radar as regulations focused on industrial point sources.

Early smoke management tools involved very simplistic representations of smoke, constant weather and a Gaussian plume (Lavdas, 1996). While this approach was adequate in the past for examining immediate, local smoke impacts when used within a systematic approach to smoke screening (Mobley et al., 1976). An increasing population is bringing more people into contact with what were previously wildlands, but is now the wildland-urban interface. The simple smoke management tools are strained by the decreasing tolerance of smoke by the increasingly impacted population and tightening air quality regulations.

Over the past ten years a number of new tools have emerged for land managers to use in managing smoke that utilize the latest technology in meteorological and smoke modeling. Achtemeier (2001) has described a local smoke model design to predict the nocturnal movement of smoke, a frequent source of roadway hazard. The BlueSky smoke modeling framework developed by the US Forest Service Pacific Northwest Research Station (Ferguson, 2001; Ferguson et al., 2001) models the three dimensional transport of smoke and provides estimates of ground level PM2.5 concentrations that can be interpreted to assess either health visibility problems. While these tools help land managers address a number of the emerging smoke management issues, they are not designed to address some of the more complex air quality issues such as regional haze and production of ozone by wildland fire emissions.

The EPA's Models 3 framework and its associated Community Multiscale Air Quality (CMAQ) modeling system provide a powerful air quality and assessment tool capable of addressing tropospheric ozone, acid deposition, visibility, fine particulate and other air pollutant issues (Byun and Ching, 1999). A key element of CMAQ is its "one atmosphere" approach that enables complex chemical interactions between atmospheric pollutants at regional scales. CMAQ is a tool developed by the regulatory community that is becoming of increasing importance to the land management community as regulatory pressure threatens to limit the use of one of their valued tools, fire.

Each of these three tools (along with others) help to address a particular aspect of the smoke management problems facing land managers; however each of these models is complex and requires a certain level of expertise to interpret and use their results. The Southern High Resolution Modeling Consortium (SHRMC), a cooperative of government and university researches, is developing the Southern Smoke Simulation System, or 4S, to integrate these tools into a cohesive framework designed to help its users make decisions. This paper presents an overview of 4S, its goals, conceptual design, system architecture and relevant research required for its implementation.

GOALS OF 4S

At its heart 4S is designed to help users perform their jobs by helping answer complex smoke management questions. "User" is a vague term that in this case can represent either a land manager, air quality regulator, public health official or the general public. Such a user group represents diverse levels of knowledge of fire and smoke management and an equally diverse set of questions that the system must be designed to address. At a general level an example set of job functions and questions which form the baseline expectations for 4S would encompass:

- Assist land managers in both the planning and operational phases of prescribed burning.
  - What weather conditions will help minimize the impact of burning on the local community?
  - Will my fire produce hazardous roadway conditions?
  - How many acres could I burn without causing any problems?
  - I had a smoke problem on my burn today, Why?

- Assist air quality regulators in assessing impact of smoke emissions and the impact of policy on prescribed fire activities.
    - What are the annual emissions from prescribed fires?
    - What would the impact of changing PM2.5 NAAQS be on prescribed burning?
    - This area had a NAAQS violation, what was the contribution of smoke?

- Assist public health and safety officials in monitoring for potentially hazardous conditions due to emissions from wildland fires.
    - Are PM2.5 or ozone levels high enough to impact sensitive populations?
    - Is smoke going to be a major issue on any roadways?

CONCEPTUAL DESIGN

Each of the above questions can be viewed as a query for data subject to constraints. Whether the user is interested in forecast or historical information, that user is interested in events that meet user defined criteria which is a perfect application for a relational database. In addition to a particular time frame, the above questions all have either explicit or at least implicit spatial scales, making the tool of choice a spatial relational database. However, the vast volume of data generated in running the associated meteorological and air quality models precludes the direct storage and query of the raw data through a database as some level of data aggregation/comparison (finding means or min/max values) is also typical of these questions.

Metadata is data about data. By analyzing the output of the various modeling components and developing a suite of metrics capable of describing events of interest to our users, a metadata database can be constructed to handle user queries and point the modeling system to appropriate data to answer their questions. Kruger et al. (2006) describe a terabyte-scale NEXRAD radar database that utilizes relational database of metadata to aid users in finding appropriate data to meet their needs. In this system as radar data is received a processing program runs a number of relevant statistics and stores the results in the database. The system allows researchers to find data specific to user specified criteria, such as cases where rainfall rates exceeded a threshold value in a particular area. 4S seeks to develop a similar system for fire weather and wildland fire emissions.

Another key concept to 4S is the delivery of a product to the user that helps them accomplish some job related task whether that be planning a prescribed burn or writing a report on PM2.5 NAAQS violation, or helping a researcher gather data for a study. "Product" is another vague term that needs to be as flexible as the definition of "user". In 4S, products are designed as data and not simply a representation of the data, such as a graph or map; although functionality for creating such representations will be available. By providing data, users can integrate 4S products into their individual workflows adding further value to 4S products. Example data products would include GIS data delivered as Web Map Services (WMS), ability to access portions of the raw weather forecast model output, emissions inventory data.

Overall 4S is conceptually driven by user needs. Examination of the needs of various user groups highlights several areas of overlap in the type, time/spatial scales of the information desired (Figure 1). By starting development in the areas of overlap we can provide a consistent user experience that hides the overall complexity of the system, but as user needs dictate that complexity can be revealed to provide the flexibility to assist the user in accomplishing their task.
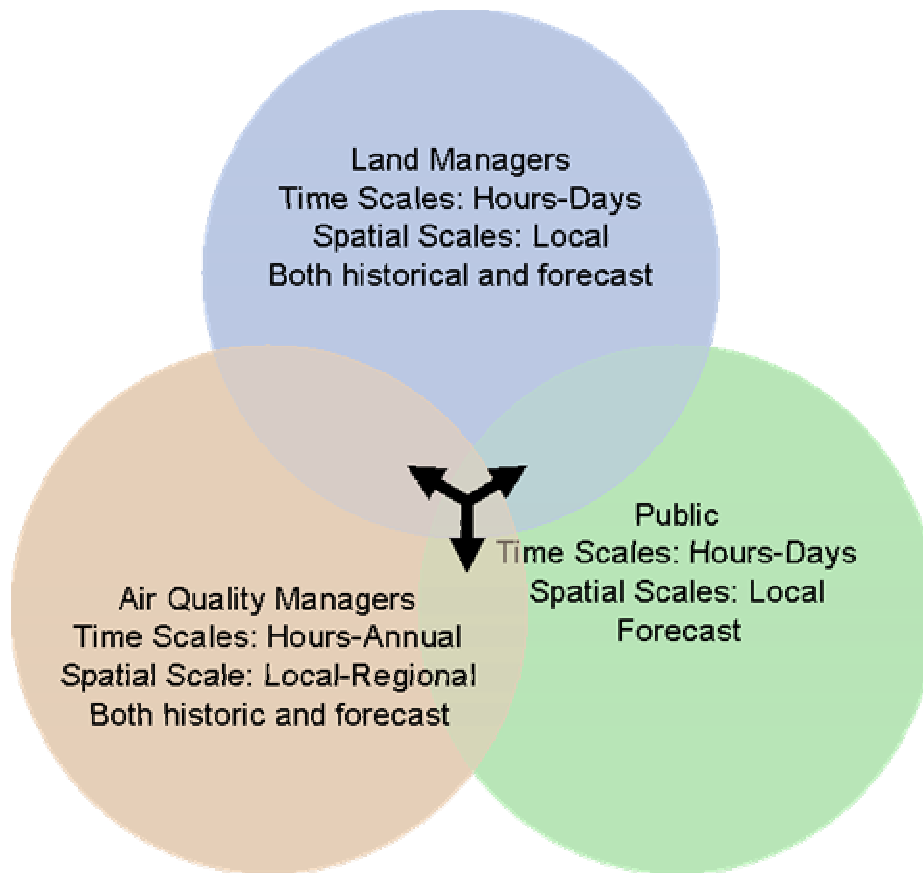
Figure 1: Conceptual diagram illustrating overlap of user group needs.

SYSTEM ARCHITECTURE

The hardware configuration of 4S involves a number of servers grouped into three classes: display, storage and computation (Figure 2). The display component is the user interface accessible through the Internet. Display components include static/dynamic web pages, image server and geospatial data server. The storage components include a data hub that will house the metadata database and coordinate the daily flow of information and act as liaison between the user and the data archive server and computation components. The data archive server will be our primary storage for data beyond a few days old. The computation components will handle running the various models (currently MM5, BlueSky and CMAQ) on both a regular schedule for real-time forecasts and an ad hoc basis to satisfy user data requests.

Data Ingest

Data from a number of external sources is required for 4S to operate. The meteorological models utilize output from forecast models run by the National Center for Environmental Prediction (NCEP) for initial and boundary conditions. Meteorological models are currently run in a forecast mode only, but plans are to also run using four dimensional data assimilation mode for the final data sets that are to be archived. The data assimilation process requires ingesting a variety of observed weather conditions for incorporation in the modeling process. The other major data source required is wildland fire data. While a national database of significant wildfires exists and can be integrate directly into 4S, prescribed fire data is more problematic. In the southeastern United States the vast majority of prescribed burning occurs on state and privately owned lands. Most states have procedures in place for authorizing prescribed burns, but not all are digital and all vary in format. SHRMC is working with individual states to integrate their fire data into 4S. Remote sensing of fire "hot spots" is an additional source for ingesting fire data, although it must be compared against other data sources to avoid double counting. All fire data will be stored along with metadata as to its source in the data archive.
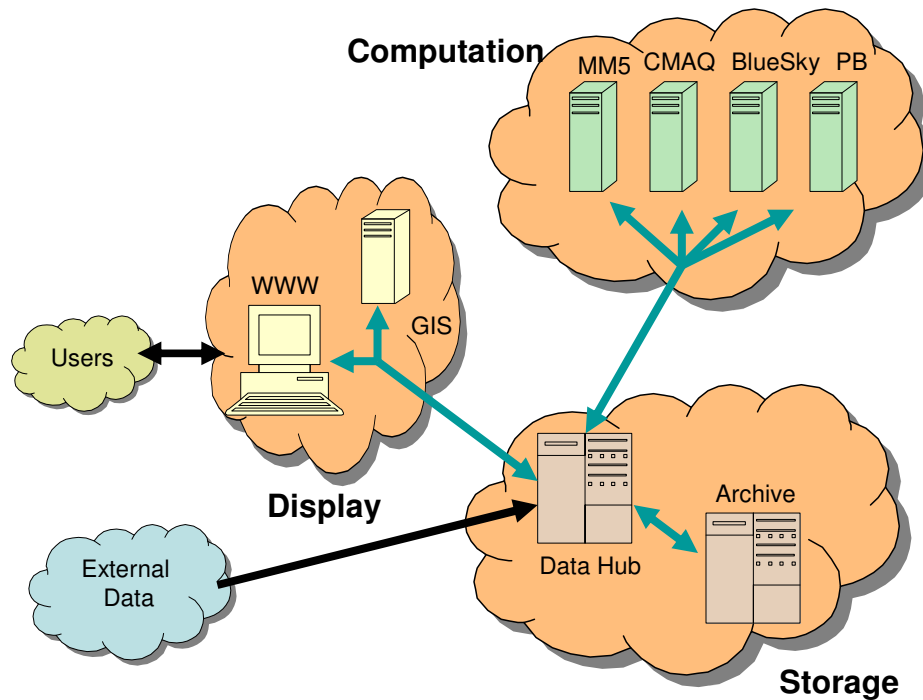
Figure 2: System architecture of 4S

Display

The user interface is the primary component of the Display layer of 4S. The user interface will be through a web browser and will make extensive use of web services to allow for an easily extensible system. By linking a series of web services together the user will be capable of producing complex analyses of the data. Sample web services will include web map and feature services for accessing GIS data, a charting service for producing graphs, a geostatistical service for performing spatial analysis using the R statistics package and a data service using UNIDATA's OPeNDAP system. By connecting user queries through a series of these services 4S will be capable of producing a wide variety of products.

Storage

The data hub is the nerve center of 4S as it sees that all other components are supplied with their requisite data and makes requests of the computational layer as needed. The data hub will host a geospatial relational database to house the metadata database. The actual calculation of the metadata will be accomplished in the computational layer. The data hub will maintain a few days of recent data for rapid access, but after this period all data will be migrated to the archive server. The archive server will host an additional geospatial relational database to store the fire activity data and provide a backup of the data hub.

Computation

The computation layer is the workhorse of 4S. This layer will be responsible for running all models in both a forecast and data assimilation mode as well as calculating metadata for model outputs. Scheduling software will be used to allocate time for user requested processing with the potential for creating ensemble output of a series of cases meeting user defined criteria. The actual models used in the systems will change with time, such as the transition from MM5 to the new WRF meteorological model. The system may be required to maintain older versions of the models to maintain compatibility when performing historical analyses.

SUMMARY

This paper has provided an overview of the Southern Smoke Simulation System currently under development by SHRMC, the Southern High Resolution Modeling Consortium. The system integrates a variety of smoke/air quality models to examine issues relating to smoke emissions at a variety of scales, from the small scale nature of nocturnal smoke movement to the regional scale. 4S is follows a user centric design by employing a modular approach that allows for the development of customized data products. Such an approach will allow 4S to hide its complexity from the user while providing flexibility and expandability.

REFERENCES

Achtemeier, G., 2001. Simulating nocturnal smoke movement, *Fire Management Today*, 61:28-33

Byun, D.W. and J. Ching, 1999. *Science algorithms of the EPA Model-3 community multiscale air quality (CMAQ) modeling system.* Research Triangle Park *NC): EPA/600/R-99/030, National Exposure Research Laboratory.

Ferguson, S. 2001. Real-time mesoscale model forecasts for fire and smoke management. *4th Symposium on Fire and Forest Meteorology,* American Meteorological Society, Reno, NV 162-167.

Ferguson, S. et al., 2001. Automated real-time predictions of cumulative smoke impactsfrom prescribed and agricultural fires. *4th Symposium on Fire and Forest Meteorology,* American Meteorological Society, Reno, NV 168-175.

Kruger, A. et al., 2006. Building a terabyte NEXRAD radar database for hydrometeorology research. *Computers and Geoscience*. 32: 247-258.

Lavdas, L.G., 1996. *Program VSmoke—Users Manual.* GTR-SRS-6. U.S. Department of Agriculture, Forest Service, Southern Research Station. Asheville, NC 156 p.

Mobley, H. et al., 1976. *Southern Forestry Smoke Management Guidebook.* GTR-SE-10 U.S. Department of Agriculture, Forest Service, Southeastern Research Station, Asheville, NC.

SRFRR, 1996. Southern Region Forest Research Report, 7th American Forest Congress, Feb. 1996.

Stanturf, J.A. et al., 2002, Background paper: Fire in southern forest landscapes, in *The Southern Forest Resource Assessment*, USDA Forest Service, SRS.

Wade, D.D. et al., 2000. Fire in eastern ecosystems. In: *Wildland Fire in Ecosystems: Effects of Fire on Flora*. Brown, J.K. and Smith, J.K. eds. GTR-RMRS-42 U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT. Chapter 4 Vol. 2. 53-96.