An Automated System for Evaluating BlueSky Predictions of Smoke Impacts on Community Health and Ecosystems

This proposal is submitted regarding: JFSP AFP 2003-1-Task3

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Abstract: BlueSky, a National Fire Plan product, provides real-time predictions of surface smoke concentrations from prescribed fire, wildfire, and agricultural burn activities to aid land managers in burn/no-burn decisions. Currently operational in the Pacific Northwest, BlueSky is a success story of what inter-agency collaboration can accomplish. One critical component of BlueSky that remains to be addressed, and that directly supports JFSP AFP 2003-1-Task3, is the development of an automated verification system to evaluate predicted impacts from smoke on communities and ecosystems. A verification system is necessary because land managers need to evaluate their burn decisions against potential National Ambient Air Quality Standard (NAAQS) exceedances, which requires a clear understanding of the accuracy of the predicted particulate matter (PM) concentration fields. We are proposing to develop this as a real-time tool to allow rapid verification and understanding of smoke dispersion models under all burn conditions.

Individual Proposing Project:

Dr. Susan O'Neill, Air Quality Meteorologist — Date

Authorizing Agency Representative:

Dr. Ed Depuit, Program Manager — Date

1. Introduction

1.1 Justification and Objectives: Predictions of smoke impacts on communities and ecosystems are currently being made by the BlueSky smoke forecast system. BlueSky provides real-time predictions of surface smoke concentrations from prescribed fire, wildfire, and agricultural burn activities. Currently operational in the Pacific Northwest, BlueSky is already a success story of what inter-agency collaboration can accomplish (Ferguson et al., 2001). One critical component of BlueSky that remains to be addressed, and that directly supports JFSP AFP 2003-1-Task3, is the development of an automated verification system to evaluate predicted impacts from smoke on communities and ecosystems. A verification system is necessary because land managers need to evaluate their burn decisions against potential National Ambient Air Quality Standard (NAAQS) exceedances. To achieve this, the verification of predicted concentrations against observed must be provided in a timely (i.e. real-time) manner. Thus two major components comprise this JFSP: 1) improving existing monitoring systems to make the data available in real-time in a manner similar to the Washington State Department of Ecology (WSDOE), and 2) implementing a software system that compares these observational data with the smoke concentration fields predicted by BlueSky. Both of these components directly support the objectives of 2003-1-Task3 by pulling together data from existing monitoring networks, improving the networks, and evaluating predicted smoke behavior with these available observational data.

1.2 Background: The Washington State Department of Ecology (WSDOE) operates a comprehensive monitoring system that obtains observations in real-time and makes them available on the web in real-time. Currently, 153 measurements are integrated into their system including wind speed, wind direction, temperature, relative humidity, PM10, PM2.5, CO, O3, NOx, SO2, and β_{scat}. The Forest Service in the Pacific Northwest is also integrating a network of nephelometer instruments into the WSDOE system. Similar functionality is necessary from other states and agencies. One of the goals of this proposal is to expand the capabilities of the other states, specifically Idaho, Oregon, and Montana and Southwestern Canada, monitoring systems to be equal to the functionality of the WSDOE system. By establishing the system and protocols in the Northwest, we hope to design guidelines that will be useful in other parts of the country.

The Montana/Idaho Airshed Group's Smoke Monitoring Unit currently accesses and downloads Particulate Matter (PM) data on a daily basis from the TEOM (Tapered Element Oscillating Microbalance) networks across Idaho and Montana. This real-time data is quality controlled using software developed specifically by the Smoke Monitoring Unit to correct and/or remove suspect 1-hour data values and recalculate 8-hour and 24-hour averages of the 1-hour PM10 and PM2.5 concentrations. The networks across these two states presently include seven PM10 TEOMS in Montana, and eight PM10 and twelve PM2.5 TEOMs in Idaho.

The daily downloads from these monitors occur between 8-10 am (Mountain Time), and involves user activated software (RPComm) developed by the manufacturer (R&P). This software currently requires manual activation due to the complex nature of the instruments and the data, although the download from the data loggers is automatic once initiated. Partial automation of the quality control software has been completed, but still requires user activated inputs and file formatting. Thus, support is necessary to further automate and improve these processes to attain a level of functionality similar to the WSDOE system.

In addition to the real-time TEOM data, the Federal Land Management Agencies (USFS and BLM) have purchased 25 DataRAM 4000 (DR-4000) Particle Monitoring Systems. These include ADSI Satellite Modems (AQD4-2000 DataRAM 4 satellite models) for uploading data through the geostationary satellite network. These are portable instruments that can be deployed in remote locations for monitoring smoke concentrations during prescribed or wildland fires.

The Pacific Northwest is home to four operational forecast systems (Table 1), two of which have a real-time verification system component. The University of Washington's (UW) Department of Atmospheric Sciences

MM5 forecast system (Mass et al., 2003 and Ferguson, 2001) contains an automated verification system comparing surface wind speeds, wind direction, temperature, and relative humidity with observations. The statistics calculated are mean error and mean bias. The AIRPACT (Vaughan et al., 2002) air quality prediction system uses the MM5 weather forecasts to predict pollutant concentrations for the Puget Sound region on a daily basis throughout the year. The emphasis is on ozone and precursors during the summer and PM and CO during the winter (http://www.airpact.wsu.edu/). AIRPACT was developed and is operated by Washington State University's Laboratory for Atmospheric Research. It also includes an automated verification system that relies on the WSDOE observational network to verify predicted ozone concentrations against observed ozone concentrations. Thus, in the Pacific Northwest we have a knowledge base to build upon to generate an automated verification system for smoke concentrations predicted by the BlueSky system (the third operational forecast system).

Table 1. Forecast Systems operating in the Pacific Northwest.

Forecast System	Operated by	Began Operation	Predicts	Scale (km)
MM5	University of Washington, Department of Atmospheric Sciences	1994	Meteorology	36, 12, 4
AIRPACT	Washington State University, Laboratory for Atmospheric Research	2000	Air quality (gas phase and primary PM species)	4
BlueSky	USDA Forest Service	2002	PM concentrations from prescribed and wild fire	12
ClearSky	Washington State University, Laboratory for Atmospheric Research	2002	PM concentrations from agricultural burning	4

The automated real-time verification system produces a wealth of information, which has allowed those working with the model to better understand the causes of model errors. With sufficient output it has been possible to begin to ferret out the causes of the well-known high surface wind speed bias exhibited by MM5. The ability to correctly characterize the precipitation bias occurring on the windward and leeward side of mountain ridges directly led to a major study to gather data regarding precipitation processes which will be used to improve existing and develop new parameterizations used in the numerical model (personal communication).

BlueSky (www.blueskyrains.org) is a National Fire Plan product developed by the USDA Forest Service in cooperation with the US Environmental Protection Agency (EPA). It is a tool for fire managers to aid in burn/no-burn decisions by providing daily predictions of where smoke plumes will occur and also providing relative areal impact information by predicting PM concentrations. Five major components comprise the BlueSky modeling framework (Figure 1). Fire characteristics are processed through the EPMv1.02 model (JFSP product) to give emission estimates of particulates ($PM_{2.5}$, PM_{10}, and total PM), carbon

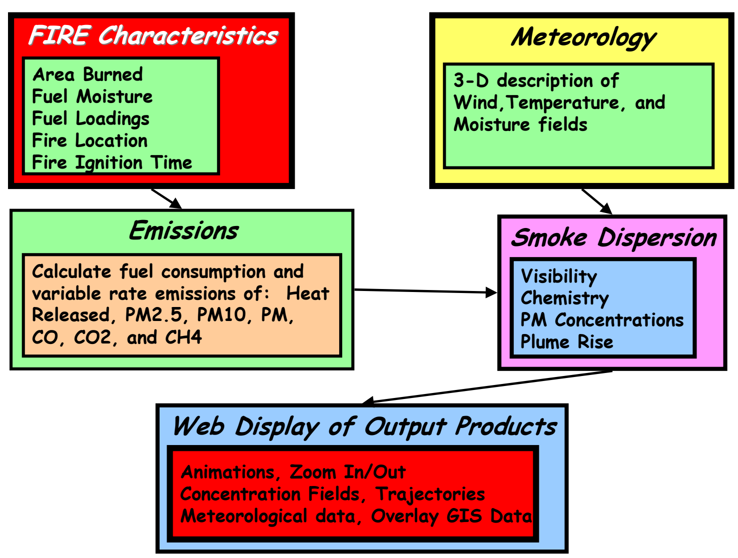

Figure 1. Components of the BlueSky system.

compounds (CO, CO_2, CH_4, NMHC), and heat generated. The emission estimates from EPM along with meteorology from MM5 are processed for the CALPUFF Gaussian dispersion model (Scire *et al*. 2000) and the HYSPLIT trajectory model (Draxler et al., 1997). CALPUFF is a puff dispersion model that simulates point, volume or area sources, assuming that plume dispersion occurs in a Gaussian pattern. CALPUFF also estimates plume rise and accounts for density differences between the plume and the ambient air. A pre-processing program, EPM2BAEM, converts the emissions from EPM into an area emission source suitable for input into CALPUFF. It calculates flame height (Cetegen *et al*.1982) using the heat-release estimates from EPM and vertical velocity of the smoke plume, assuming conservation of buoyancy flux proportional to heat-release rate. Thus, the BlueSky system framework merges meteorology with emission estimates to yield an integrated regional-scale analysis of smoke dispersion and aerosol concentrations across the Pacific Northwest.

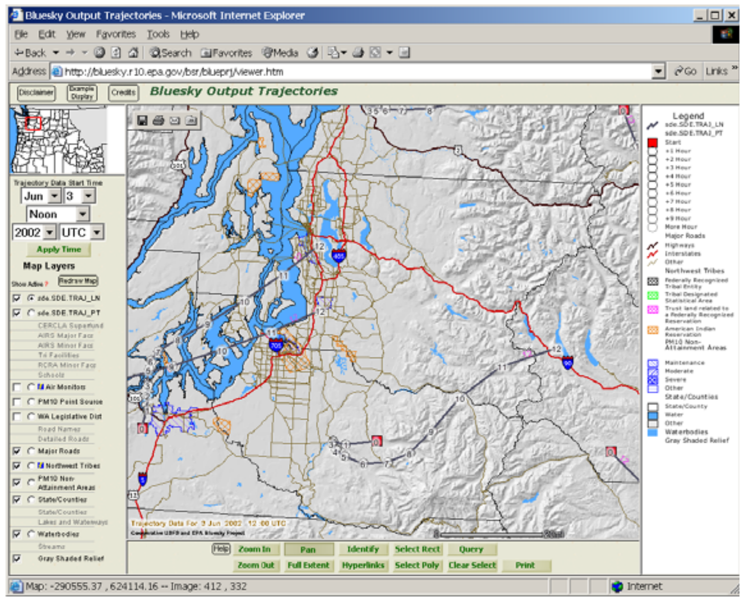

Figure 2. Twelve-hour HYSPLIT trajectories in the Puget Sound region, within the BlueSkyRAINS application, for June 3, 2002.

The BlueSky concentration fields and trajectories are displayed on the Web site in the Rapid Access INformation System (RAINS); a Geographical Information System (GIS) application developed by the US EPA. By integrating BlueSky with RAINS, the user can zoom in on areas of interest, step through time, and overlay GIS data layers such as sensitive receptors (e.g. schools, hospitals), geo-political boundaries, and topography. Figure 2 depicts trajectories from several locations in the Puget Sound region overlain with GIS layers of: major roads, Northwest Tribal locations, PM10 non-attainment areas, state and county lines, water-bodies, and gray shaded topographical relief. The trajectories are marked at hourly increments, originating at hour zero, and progressing to hour 12.

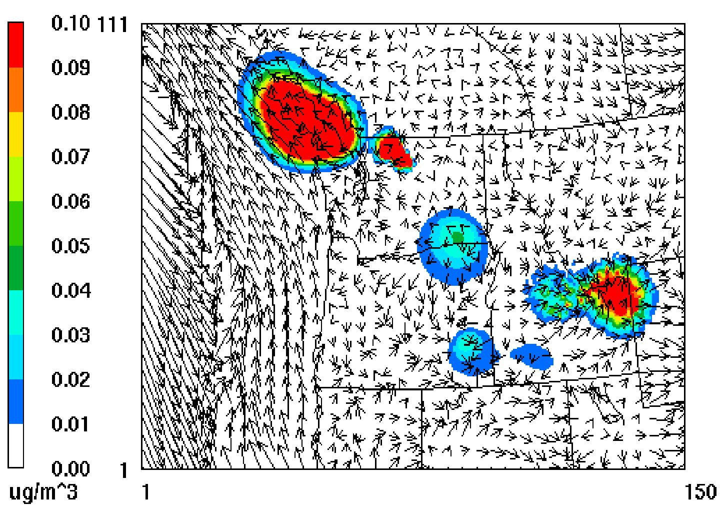

Figure 3. PM2.5 concentrations predicted by the BlueSky smoke dispersion system for October 23, 2002 at 5 pm PST for the Pacific Northwest. Prescribed burn information provided by FASTRACS.

BlueSky is a success story in the Pacific Northwest where it has been operational since July 2002, running on a 12 km domain using the University of Washington's MM5 forecast data and the Fuel Analysis, Smoke Tracking, Report Access Computer System (FASTRACS); a prescribed burn reporting system. Figure 3 shows smoke dispersion patterns across the Pacific Northwest for October 23, 2002, a day when 23 prescribed burns were reported in the FASTRACS system. BlueSky also aided land managers monitoring the Quartz Complex wildfire for confinement strategy in the Pasayton wilderness of Washington State. In a related JFSP, BlueSky will be implemented in other regions shown in Figure 4, via the Fire Consortia for the Advanced Modeling of Meteorology and Smoke (FireCAMMS).

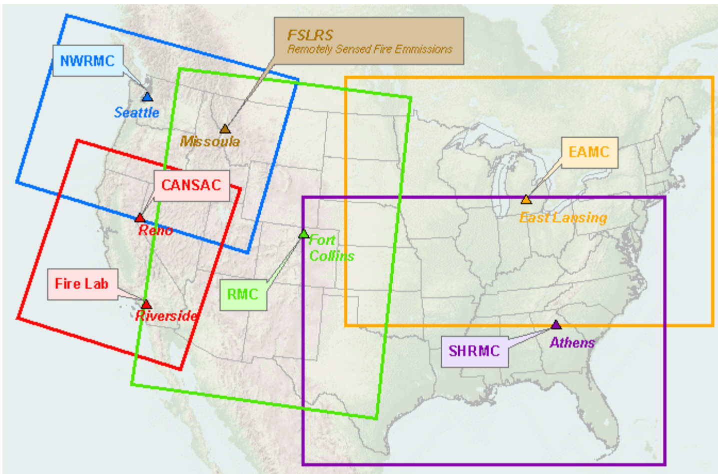

Figure 4. The five Fire Consortia for the Advanced Modeling of Meteorology and Smoke (FireCAMMS) domains in which the BlueSky system will be implemented.

BlueSky is also in the process of integrating with the ClearSky (www.AIRPACT.wsu.edu/ClearSky/index.html) agricultural burning smoke prediction system developed by the Laboratory for Atmospheric Research at Washington State University under contract to the State of Idaho. ClearSky is the fourth operational forecast system in the Pacific Northwest. The ClearSky project is an experimental application of the CALPUFF plume dispersion model, employed in a forecast system to support local smoke managers in Idaho's Kootanai and Benewah counties. ClearSky allows these managers to generate field-burning scenarios and review the resulting CALPUFF simulation results through the project website prior to making burn decisions. The ClearSky system was operated on a daily basis during the August through September 2002 burn season. It is now being expanded to include all of Washington State and to incorporate the WADOE real-time observations as part of a real-time verification system for agricultural smoke.

The PM concentration predictions made by BlueSky and ClearSky currently are not evaluated, and thus serve only as an indication of relative smoke impacts on communities and ecosystems. Evaluation is necessary if land managers are to use this tool to avoid potential exceedances of the National Ambient Air Quality Standards (NAAQS). Furthermore, a real-time system will provide in a timely manner a measure of how well various locations/regions are complying with federal and state ambient air quality standards and visibility impairment measures. Having tools such as these in use by land managers is unprecedented. Nowhere else in the country is there a real-time system evaluating impacts from smoke on communities and ecosystems. Furthermore, given the extensibility of the BlueSky system, this capability will transfer to other regions across the US.

The goal of this verification system is to evaluate instances of air quality degradation, in terms of PM concentrations and visibility degradation, as defined by the NAAQS and the Regional Haze Rule. The NAAQS were originally defined for six criteria pollutants: SO2, NO2, O3, PM10, Lead, and CO. Regulations have recently been promulgated tightening the standards for some pollutants (such as ozone and PM10) and enforcing new standards for PM2.5 concentrations. Table 2 summarizes the NAAQS (new and old) for PM2.5 and PM10.

Table2. National Ambient Air Quality Standards (NAAQS) for PM10 and PM2.5.

Pollutant	**Concentration**	**Units**	**Averaging Time**
TSP (old standard)	260	$\mu g/m^3$	24 hour
PM10 (existing standard)	50	$\mu g/m^3$	Annual
PM10 (existing standard)	150	$\mu g/m^3$	24 hour
PM2.5 (new standard)	15	$\mu g/m^3$	Annual
PM2.5 (new standard)	65	$\mu g/m^3$	24 hour

Visibility degradation is an issue both in rural areas and in Class I wilderness areas where the Regional Haze Rule establishes that visibility must remain at natural or background levels. Visibility degradation is caused by aerosols and gases in the atmosphere scattering and absorbing light. The net extinction of light in units of inverse megameters (1/Mm) is:

$$b_{ext} = b_{sg} + b_{sp} + b_{ag} + b_{ap} \quad (1)$$

where: b_{ext} = extinction coefficient (1/Mm)
b_{sg} = light scattering due to gasses (1/Mm)
b_{sp} = light scattering due to particles (1/Mm), also referred to as β_{scat}
b_{ag} = light absorption due to gasses (1/Mm)
b_{ap} = light absorption due to particles (1/Mm)

NO2 is the primary gas specie responsible for light absorption and is usually negligible except in urban atmospheres. Raleigh scattering is the scattering of light by gases in the atmosphere. The "baseline" definition of clean pristine conditions includes Raleigh scattering and an estimate of the natural aerosols and is the measure against which degradation is determined. Absorption of light by aerosol particles accounts for 5% (rural) to 50% (urban) of visibility impairment and conversely, light scattering by aerosol particles contributes between 95% (rural) to 50% (urban) of visibility impairment. Thus, in rural areas, scattering of light by aerosols in the atmosphere is the primary source of visibility impairment. Nephelometers measure this scattering of light by aerosols (β_{scat}).

The deciview (dv) is a useful means of describing visibility because it linearizes the extinction coefficient such that a 10% increase in extinction corresponds to a deciview increase of one. The deciview is calculated by:

$$dv = 10 \ln (b_{ext}/10) \quad (2)$$

where b_{ext} is in units of 1/Mm. Under pristine conditions the deciview has a value of zero. Deciview values in the range of 20-30 are indicative of hazy conditions.

This JFSP develops and supports the infrastructure necessary to obtain measurements in a timely manner so that land managers can evaluate smoke impacts on ecosystems and communities. It also expands the utility of the measurements by using them to evaluate a system that predicts smoke impacts on communities and ecosystems. Utilizing a real-time monitoring network to evaluate predictions of smoke concentrations made by the BlueSky system will provide a measure of how well BlueSky predicts exposure of communities and ecosystems to smoke. Thus, not only does the work outlined in this JFSP make smoke exposure information available in real-time, but builds a system that will provide confidence in predictions of what that smoke exposure could be.

2. Materials and Methods

Two objectives comprise the work proposed here:
Objective 1) Improve existing smoke measurement systems to obtain the observational data in real-time. Make all observational data available on the world-wide-web.
Objective 2) Develop a real-time software system that compares observational data with the smoke concentrations fields predicted by BlueSky.

2.1 Objective 1: Improve existing smoke measurement and burn reporting systems

2.1.1. Improve existing smoke measurement systems: Using the State of Washington's Department of Ecology's real-time access to observational data as a prototype, we will work with federal and state agencies in the states of Oregon, Idaho, and Montana, to obtain observational data in a real-time manner and display the data on the web. Specifically, we propose significant upgrades to the real-time access, quality control and analysis of the PM monitoring data in Idaho and Montana. The upgraded system will allow for data acquisition by the BlueSky modeling system. In addition, improved quality control analysis is needed to ensure the PM concentrations meet EPA and DEQ data quality standards. The improvements will require significant software development and rigorous testing before they can be used in an operational setting. The following is a list of tasks and project requirements:

1. Automation of the daily (4-times/day) data acquisition from Idaho/Montana TEOM networks.
2. Automation and improvements to the quality control software of real-time TEOM data.
3. Development of a web-based system for accessing real-time Idaho/Montana TEOM data.
4. Automation of the web-based system for displaying real-time TEOM data.

2.1.2. Improve burn reporting within BlueSky: Accurate predictions of smoke concentrations can only be made if all available burn information is utilized in BlueSky. Efforts are currently underway to automate the incorporation of the Montana/Idaho Airshed's burn reporting system data into the BlueSky system for the Pacific Northwest. Similar effort is necessary to incorporate the State of Washington's Department of Natural Resource's (DNR) reported burn data.

2.2 Objective 2: Development of a real-time evaluation system

2.2.1 Correlate PM2.5 concentrations with nephelometer data. Three approaches will be taken:

1. Calculate the correlation coefficient (r^2) between measured β_{scat} and predicted PM2.5 concentration.
2. Convert β_{scat} to deciview, to linearize the β_{scat} scale, and calculate r^2 between deciview and predicted PM2.5 concentration.
3. Conversions from β_{scat} to PM2.5 concentration are available when the particular nephelometer model's measurements have been correlated with a federal reference method (FRM) instrument. When such a conversion is provided for a particular location, calculate the r^2 between the β_{scat} derived PM2.5 concentration and the predicted PM2.5 concentration.

2.2.2 Apply a suite of traditional statistical measures to compare predicted smoke concentrations with the observed smoke concentrations from TEOM and HIVOL instruments. Specifically, calculate: mean, standard deviation, index of agreement, mean error, normalized mean error, bias, normalized bias, correlation coefficient.

The index of agreement is calculated by:
$$I = 1 - \frac{\sum_{i=1}^{N}(p_i - o_i)^2}{\sum_{i=1}^{N}(|p_i - \bar{o}| + |o_i - \bar{o}|)^2} \qquad (3)$$

where, p_i and o_i are the predicted and observed concentrations respectively for measurement *I*, N is the total number of measurements, o denotes the average observed concentration, and a value of 1 indicates perfect agreement between predicted and observed values

The bias is calculated by:
$$B = \frac{1}{N}\sum_{i=1}^{N} p_i - o_i \qquad (4)$$

The error is calculated by:
$$E = \frac{1}{N}\sum_{i=1}^{N} |p_i - o_i| \qquad (5)$$

The normalized bias is calculated by:
$$B = \frac{1}{N}\sum_{i=1}^{N} \frac{p_i - o_i}{o_i} \qquad (6)$$

The normalized error is calculated by:

$$E = \frac{1}{N}\sum_{i=1}^{N}\frac{|p_i - o_i|}{o_i} \qquad (7)$$

where a normalized error of 35% and a normalized bias less than +/- 15% are suggested by EPA as indicative of acceptable ozone modeling performance. Similar bounds are not yet available for PM modeling performance.

2.2.3 Investigate trends and relationships between the observations and the predictions. Box & whisker plots can be to illustrate gridded heterogeneity by comparing the observed value with predicted values for the three-by-three square of cells surrounding the observation. Since the above statistical measures contain no information that can be used to evaluate the reasons for poor model performance, several other comparisons will be made involving model performance (often expressed as the ratio of model predicted to observed) as a function of other variables such as time of day, general soil conditions, general fuel moisture, ambient temperature, wind speed, ... These comparisons can be made for any combination of predicted and observed parameters as functions of other parameters that are thought to affect emissions, wind fields, or observations, for that matter. After one or more years of evaluation, sufficient information will be available to suggest areas in the modeling system that need changing to improve model performance.

2.2.4 Display the statistics including their spatial variability and observed and predicted concentration time series on the web.

3. Project Team

We have put together an interagency and interdisciplinary team that is well positioned to undertake the work outlined in this proposal. Dr. Sue Ferguson and Rob Wilson were the brains behind the inception of BlueSky, Dr. Brian Lamb is a recognized leader in air quality research, Dr. Joe Vaughan has developed both the AIRPACT and ClearSky forecast systems, Clint Bowman and Dick Stender have years of experience in air quality issues from a regulatory standpoint, Dr. Dave Levinson leads the MT/ID Airshed Group and as such has a thorough knowledge from a user standpoint of what a smoke concentration prediction system needs, and Dr. Susan O'Neill has studied under Dr Brian Lamb and is now project lead of the BlueSky project.

Personnel	Responsibility
Susan O'Neill – USDA Forest Service, PNW Station	CO-PI, project management, BlueSky system management, smoke dispersion modeling, communication
David Levinson – BLM, MT/ID Airshed Group	CO-PI, burn manager, communication
Brian Lamb – Washington State University	CO-PI, project management, air quality researcher, model evaluation, communication
Clint Bowman – Washington State Department of Ecology	CO-PI, meteorologist, atmospheric scientist, project management, air quality regulator, model evaluation, communication
Sue Ferguson – USDA Forest Service, PNW Station	CO-PI, project management, meteorology/smoke researcher, communication
Dick Stender - Washington State Department of Ecology	Collaborator, burn manager, meteorology, air quality regulator, communication
Rob Wilson – US EPA Region 10	Collaborator, meteorologist, air quality regulator
Joe Vaughan – Washington State University	Collaborator, air quality researcher, model

	evaluation, communication
Narasimhan Larkin – USDA Forest Service, PNW Station	climate modeling, verification system design, communication
Adam Rhoads – BLM, MT/ID Airshed Group	Monitoring data
Steve McKay – USDA Forest Service, PNW Station	Statistical analysis, verification system design, communication
Alesha Morgan – USDA Forest Service, PNW Station	Statistical analysis
Jeff Silverman – USDA Forest Service, PNW Station	Computer system support
Candace Berg – USDA Forest Service, PNW Station	Statistical analysis
Mitchell Johnson – USDA Forest Service, PNW Station	Web products

4. Deliverables

1. Real-time web-accessible monitoring network integrating data from the states of Washington, Oregon, Idaho, and Montana and from federal agencies such as the USDA Forest Service and Bureau of Land Management.

2. A software system that reads in gridded smoke concentration fields in netCDF format, extracts concentration time series at the monitoring site locations, and statistically compares the observations with the predictions. The observations will be read from a real-time monitoring network across Washington, Oregon, Idaho, and Montana.

3. Scientific publications, including peer-reviewed journals (Atmospheric Environment, International Journal of Wildland Fire), evaluating the performance of the BlueSky smoke prediction system with observations over a suite of burn seasons.

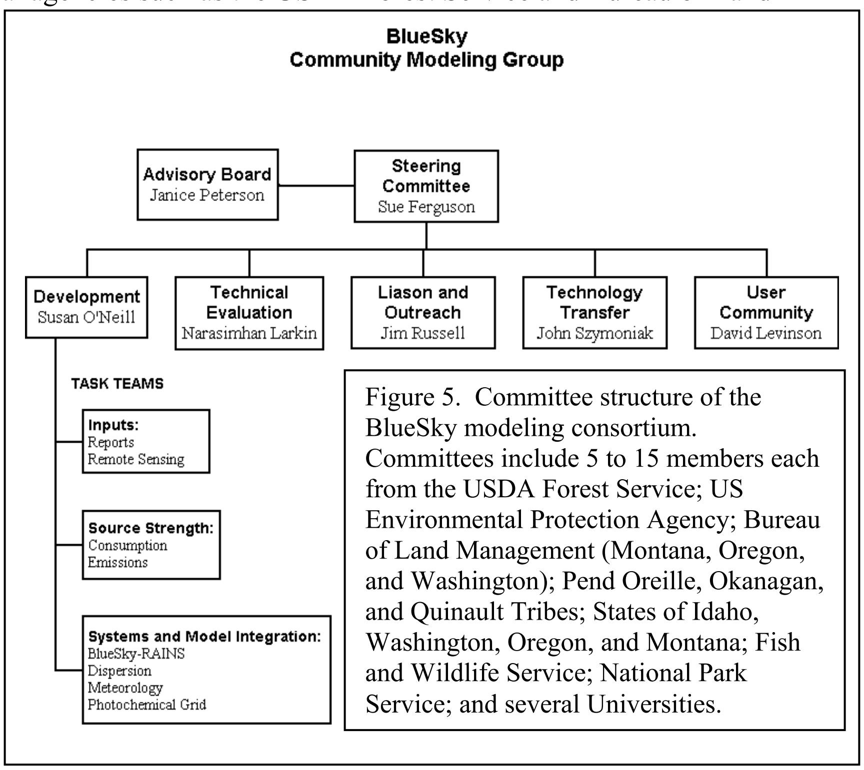

Figure 5. Committee structure of the BlueSky modeling consortium. Committees include 5 to 15 members each from the USDA Forest Service; US Environmental Protection Agency; Bureau of Land Management (Montana, Oregon, and Washington); Pend Oreille, Okanagan, and Quinault Tribes; States of Idaho, Washington, Oregon, and Montana; Fish and Wildlife Service; National Park Service; and several Universities.

5. Technology Transfer

A significant amount of technology transfer occurs through the multi-agency BlueSky smoke modeling consortium (Figure 5). The BlueSky smoke-modeling framework is a community development project that was born out of a multi-agency smoke modeling meeting in July 2000. Agencies represented by the community of members include the USDA Forest Service Regions 1 and 6, Fire Vision Enterprise, Rocky Mountain Research Station, and the Pacific Northwest Research Station; the Bureau of Land Management, Washington, Oregon, and Montana; the States of Oregon, Washington, Montana, and Idaho; the Environmental Protection Agency; Pend Oreille, Okanagan, and Quinault Tribes; Fish and Wildlife Service;

National Park Service; and several Universities. Members include managers and scientists who meet at least annually with subcommittees meeting more often to review, discuss, and help direct the development of BlueSky functions and attributes.

The work proposed here is the direct result of concerns expressed by the BlueSky consortium, who need methods of evaluating the accuracy of smoke dispersion models and using model output to evaluate impacts of smoke on NAAQS. All members of the consortium will be responsible for reviewing and guiding both the technical aspects of this project as well as output products. In addition, members will be asked to help craft guidelines for interpreting and using the verification results.

In addition to the BlueSky consortium's ability to assist in the transfer of technology within the northwestern U.S., the BlueSky project is a member of the Fire Consortia for Advanced Modeling of Meteorology and Smoke (FireCAMMS). Multi-agency consortia in all regions of the contiguous states have been fashioned after BlueSky's and are embarking on similar modeling and user-support projects. As a result, results from this project will become part of the BlueSky package that is being implemented in other regions.

Particular technology transfer products include:

- Web products that show the location and value of *observed* gases and particulates in hourly, 8-hour, 24-hour, and annual increments, compared to OSHA and NAAQS standards.
- Web products that show the location and value of *modeled* gases and particulates in hourly, 8-hour, 24-hour, and annual increments, compared to OSHA and NAAQS standards.
- Web products that show the timing and location of model *errors* as compared with observations.
- Manual for land management users that explains how to view and interpret the results.
- Bundled software and installation guidance for implementation of the verification system and other BlueSky components in all FireCAMMS regions.
- Manual for technical users that describes how to integrate various monitoring stations or networks into the verification system.
- Guidance on how to improve modeling dispersion of smoke from wildland fires.
- Device-independent maps of observations, model output, and verification results that can be exported from the BlueSky-RAINS website into local ArcInfo projects to facilitate reporting and overlaying with local databases.

Conference proceedings and journal articles that describe the validity of modeling dispersion of smoke from wildland fire.

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