AN EVALUATION OF MODELED PLUME RISE WITH SATELLITE DATA

Sean Raffuse*, Katie Wade, Jordan Stone, Dana Coe Sullivan, and Neil Wheeler
Sonoma Technology, Inc., Petaluma, CA, USA

Narasimhan Larkin, Tara Strand, and Robert Solomon
USDA Forest Service AirFire Team, Seattle, WA, USA

1. INTRODUCTION

During the past decade, both the number and the intensity of wildfires in the western United States have increased (Westerling et al., 2006). As a result, attention has been focused on modeling and forecasting smoke impacts from wildfires, and efforts are being made to improve existing smoke modeling and forecasting systems. Smoke modeling systems generate predictions of surface concentrations of aerosol particles and gases and are often used to estimate smoke impacts on human health.

Plume rise, the elevation attained by a rising smoke plume, is an important parameter that affects the dispersion of smoke and ground-level air pollutant concentrations. Plume rise is currently a large source of uncertainty in air quality models that predict smoke impacts from wild fires. The miscalculation of plume rise from large fires can result in downwind air pollutant concentration predictions that can be incorrect by an order of magnitude (Larkin et al., 2009).

The objective of this work was to use satellite observations of smoke plume heights from wildfires to better understand real-world smoke plume characteristics and the source(s) of uncertainties associated with plume height algorithms commonly used in existing air quality models.

2. BACKGROUND

Transport and dispersion of smoke from wild fires is difficult to model accurately. A key driver of the transport and dispersion of smoke is thermal energy which is produced when biomass is consumed. Thermal energy creates buoyancy which causes smoke particles and other pollutants to rise above a fire. The height that is attained by a rising plume of smoke is referred to as plume height and is a function of both heat release rate and ambient weather conditions, although heat release dominates. The heat release rate is almost directly related to the fuel consumption rate. Unfortunately, estimates of fuel consumption for a given plume are highly uncertain in existing modeling systems.

Algorithms used to describe plume rise and buoyancy in commonly used modern-day dispersion models were developed in the 1960s to characterize industrial emissions from tall smoke stacks (Briggs, 1969). These algorithms are still used to estimate the plume rise and buoyancy of fires despite the physical differences between smoke stacks and wildland fires. Heat released from industrial stacks is more straightforward to estimate because it is generally produced from the steady-phase combustion of a single fuel such as coal or natural gas and is emitted into the atmosphere at a relatively constant rate, and the parameters of the system are often well known. Emissions from fire can be highly variable in both time and space (Breyfogle and Ferguson, 1996). Fuel consumption rate (thus heat released) from fires is a function of several variables including vegetation (fuel) type and loading, fuel conditions, and ignition method. Moreover, the amount and rate of heat release from fires varies by combustion phase (i.e., pre-ignition, flaming, smoldering, and residual), making it more difficult to estimate. In addition, plumes emitted from industrial stacks have different characteristics than plumes emitted from wildfires. Plumes from industrial stacks create single convective columns that rise high above the ground while plumes from wildfires tend to create broadly distributed, cohesive plumes that initiate just above the ground and rise to elevated levels. Even if all the parameters for a specific burned area required to model total heat release are well known, modeling plume rise is difficult because burns often occur over a large area and may form multiple plumes, splitting the total heat into several plume cores.

Plume rise greatly affects the distance that smoke aerosols are transported. Plumes attaining elevations greater than the tropospheric boundary

Corresponding author: Sean Raffuse, Sonoma Technology, Inc., 1455 N. McDowell Blvd., Suite D, Petaluma, CA 94954-6503; e-mail: sraffuse@sonomatech.com

layer (approximately 0.8–1 km above the earth's surface, depending on atmospheric conditions) are often transported hundreds to thousands of kilometers downwind. In contrast, smoke plumes remaining within the boundary layer become well mixed in regions relatively near the fire (Kahn et al., 2007). The vertical distribution of emissions is a key input to and driver of dispersion models; therefore, accurately characterizing smoke plumes and their vertical structure is required to produce useful regional- and national-scale smoke prediction model results.

3. METHODS

In this study, observed plume height data collected by two different satellite instruments were compared to plume height information from smoke model predictions for a large number of fires that occurred from 2006 through 2008 in the United States (US).

Data from the Multi angle Imaging Spectro Radiometer (MISR) instrument onboard the Terra satellite and data from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite were used for this analysis. Both instruments measure plume heights in distinct and complementary ways. The MISR relies on stereoscopic analysis of plumes based on a minimum of two angular views to extract plume heights (Kahn et al., 2007). The CALIOP uses active lidar to measure aerosol vertical profiles (Young and Vaughn, 2009).

The overall approach for this work involved four general steps: (1) data acquisition and processing, (2) identification of fires and corresponding CALIOP and MISR satellite observations, (3) development of the modeled smoke predictions for comparison to the satellite observations, and (4) comparison and assessment of the modeled plume height predictions to the satellite observations.

3.1 Data

The following is a summary of the data used for this study:

- The Hazard Mapping System (HMS) Smoke Product was used to identify locations and times when smoke plumes were present during 2006-2008 (McNamara et al, 2004).
- The Satellite Nadir Track Sensor Observation Service provided by the Vis Analysis Systems Technologies team at the University of Alabama in Huntsville (http://vast.uah.edu) was used to determine CALIPSO orbit paths and identify days when the CALIPSO orbit intersected a smoke plume in the HMS data set.
- CALIOP Lidar Level 2 5-km aerosol data acquired from the Atmospheric Science Data Center (ASDC) (http://eosweb.larc.nasa.gov/PRODOCS/calipso/table_calipso.html) were used to compare observed smoke plume heights to modeled plume heights.
- CALIOP Lidar Level 1B wavelength backscatter profile data acquired from the ASDC were used for data visualization and qualitative assessment.
- Smoke plume summary data acquired from the MISR Plume Height Climatology Project (http://www-misr2.jpl.nasa.gov/EPA-Plumes/) were used to compare observed smoke plume heights to modeled plume heights (Nelson et al., 2008).
- Daily fire locations from the SMARTFIRE fire information system (Raffuse et al., 2006) were used to identify the latitudinal and longitudinal locations of fires and burn area data corresponding to the same days and times of the MISR plume heights, HMS smoke plumes, and CALIOP measurements.
- The BlueSky framework smoke modeling system was used to develop modeled smoke plume height information for comparison to the CALIPSO and MISR satellite observations (Larkin et al., 2009).

3.2 Identification of Fires and Corresponding Satellite Observations

The MISR plume height database and the CALIOP aerosol profiles represent two discrete sources of plume height information with little overlap. Because of their differences, separate approaches were employed for each.

MISR plumes were matched to fires from the SMARTFIRE database. SMARTFIRE integrates and reconciles human-recorded wildfire incident data from Incident Status Summary (ICS-209) reports with satellite-detected fire data and serves as the fire location and area burned source for the modeling in this study. Matched MISR/SMARTFIRE pairs were determined by selecting the nearest same-day fire location in the SMARTFIRE database that was greater than 40 hectares in size

Because of the very narrow swath width of the CALIOP instrument, observations of smoke plumes close to the fire are rare. We developed an automated routine to determine the locations and times when the CALIPSO orbit intersected smoke plumes. Daily CALIPSO orbit path data were overlaid with daily HMS smoke plume data for 2006-2008, and the geographic intersection points were noted as potential candidate times and locations when the satellite was likely to detect a smoke plume.

3.3 Development of Modeled Smoke Predictions

The BlueSky modeling framework was used to construct the modeling pathway and to create the output data sets for comparison to the MISR and CALIOP observations. The BlueSky framework links many different sub-models together to produce emissions and pollutant transport estimates from wild and prescribed fires. To produce emissions estimates, BlueSky requires fire location and size information. SMARTFIRE was used to produce this information.

Emissions factors were modeled using the Fire Emission Production Simulator (FEPS), which uses the consumption information to modulate emission factors based on combustion efficiencies. The results of this modeling were hourly emissions and heat release rates per fire. The hourly heat release rates were fed into the plume rise calculator in FEPS (built into the BlueSky framework), which is an adaptation of the Briggs plume rise algorithm, resulting in hourly estimates of plume top and plume bottom for each fire.

The Community Multiscale Air Quality (CMAQ) model (National Exposure Research Laboratory, 1999) version 4.5.1 was used to estimate three-dimensional fields of $PM_{2.5}$ concentrations from fires on the national 36-km Regional Planning Organization (RPO) grid, covering the continental US. The CMAQ model simulations are driven by meteorological data generated by the Pennsylvania State University (PSU) National Center for Atmospheric Research (NCAR) mesoscale model (MM5) (Grell and Stauffer, 1994) version 3.7. MM5 modeling is performed on a 29-layer vertical grid, with vertical resolution of 50 to 75 m in the lower troposphere gradually stretching to coarser resolution at the upper layers of the grid. CMAQ modeling is performed on a 17-layer vertical grid, which maps to the MM5 vertical grid.

3.4 Comparison of Modeled Plume Heights to Observed Plume Heights

Statistical analyses were performed across all data points to compare how well the observed plume heights from the MISR data agreed with the modeled plume heights and how well the observed CALIOP aerosol profiles agreed with the CMAQ modeled plume height equivalents. Basic statistics (i.e., mean, median, standard deviation, etc.) were calculated for each data set. A Kolmogorov-Smirnof test was performed to determine statistical significance. The data sets were also analyzed by region to determine how well the observed data compare to modeled data in different regions of the US. MISR-to-model comparisons were further segregated by parameters that drive the plume rise calculations, such as area burned and fuel loading.

4. RESULTS

4.1 Comparison of MISR Observed Plume Heights to Modeled Plume Heights

The results of the comparisons between the MISR-observed plume heights and the modeled plume heights show that over all the data points, the observed median plume-top height is statistically significantly higher than the modeled plume-top height. **Table 1** shows the results of the statistical comparisons. The median and mean modeled plume height was lower than the observed plume height. The range of the modeled plume height was much larger than the range of observed plume heights, indicating more overall variability in the modeled plume heights. A Kolmogorov-Smirnof test confirmed that the two distributions were significantly different.

While there was no statistically significant relationship between observed and modeled plume heights when all data values were considered, the spatial distribution of plume heights between the observed and modeled data agree fairly well. In general, fires in the southeastern US produce much lower plume heights than those in the western US. Further analyses were performed to quantitatively compare plume heights by geographic region.

Table 1. Results of the statistical comparison of observed plume heights from the MISR instrument and modeled plume heights. Plume height units are meters above ground surface level.

Parameter	MISR Plume Height Observations	Modeled Plume Height
N of samples	163	163
Minimum	284	109
Maximum	5,088	18,699
Median	1,436	806
Mean	1,700	1,557
Standard deviation	1,125	2,116

The regional comparisons indicated that the difference between the observed and modeled plume heights was exaggerated in the mountain and Pacific Northwest regions of the US where the median observed plume heights were statistically significantly greater than the modeled plume heights. However, in regions such as the southeastern US, the difference between the observed and modeled plume heights was not statistically significant. One notable finding is that, despite the lower median modeled plume height, the modeled plume height was several times higher than the observed plume height of several fires in the northwestern US and in Kansas. **Figure 1** is a map of fire locations and corresponding plume height data from the modeled and observed data.

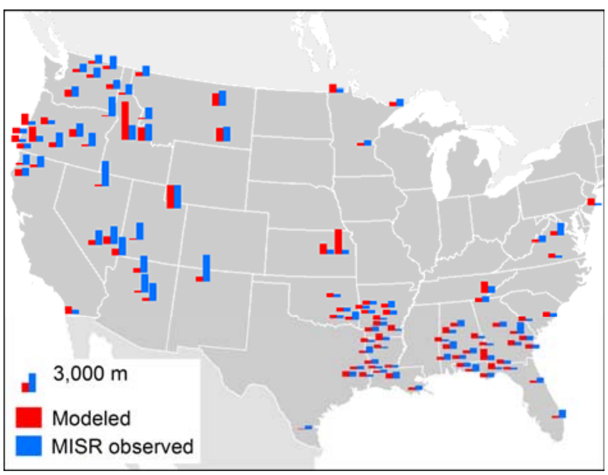

Fig 1. Map of fire locations and corresponding plume height data from the modeled (red bars) and observed (blue bars) data.

4.2 Comparison of CALIOP Observed Plume Heights to Modeled Plume Heights

The median modeled plume height equivalent was statistically significantly lower than the median CALIOP observed plume height. The range of plume height values was similar; however, the distribution of plume height values was statistically significantly different based on a Kolmogorov-Smirnof analysis which yielded a P-value of 0.005. A weak positive correlation was observed between the CALIOP observed plume height and the modeled plume height (R^2=0.22); however, there was significant scatter in the results. **Figure 2** shows the results of the regression analysis of the CALIOP observations (x-axis) and the modeled plume height data (y-axis).

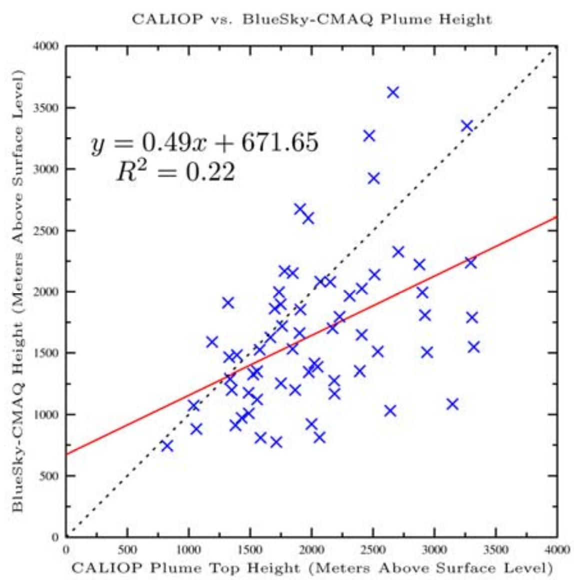

Fig 2. Results of the regression analysis of the CALIOP observations (x-axis) and the modeled plume height data (y-axis). Units are meters above ground level.

5. DISCUSSION AND CONCLUSIONS

We compared plume rise estimates from a near real-time predictive modeling system to an MISR-derived database of plume heights and CALIOP aerosol vertical profiles. On average, our modeled smoke plume heights were lower than the observed plume heights from both MISR and CALIOP. We compared modeled plume top estimates directly with median wind corrected plume heights from MISR. The modeled plume tops exhibited much greater variability than the MISR heights, and there was no significant correlation between the two data sets. We also fed our plume tops into a chemical transport model and compared the resulting vertical profiles with CALIOP aerosol data. These data were weakly correlated, and the modeled plume heights were lower than the CALIOP heights.

When examined regionally, the difference between observed and modeled plume heights of fires that occurred in the southeastern US was not statistically significant. However, observed and modeled plume heights in the northwestern US were statistically significantly different. In addition, under certain circumstances, modeled plume heights of fires in the northwestern US were extremely high. These plume height differences tend to occur when the size of a fire, or the area burned, is very large.

The regional differences in observed and modeled plume heights do not appear to be solely the result of vegetation and fuel loading. In the southeastern US, fires tend to be relatively small, and many fires are controlled or prescribed burns. Small and/or controlled burns behave relatively well and are less variable than larger, uncontrolled fires. Fuel moisture in the southeastern US is higher resulting in lower burn efficiency which, in turn, results in less heat release and smaller, less intense fires. Because the factors that affect plume height tend to be less variable and are more bounded, the plume height algorithms perform relatively well for fires in the southeastern US.

Burn areas of fires in the northwestern US tend to be much larger, with lower fuel moisture and more diverse vegetation, or fuel loading. Fires with large burn areas and overall low fuel moistures produce significant heat which greatly affects plume height in the plume rise algorithms. Because the Briggs plume height algorithm was developed to model plumes from industrial stack-like sources, when applied to fires, it treats the emissions from fires as if they are injected into the atmosphere from a single point location. This scenario is physically inaccurate for fires with large burn areas and smoke plumes that can be low to the ground and emanate from multiple locations across the burn area as a fire grows and spreads.

The plume height equivalent data from the CMAQ model showed somewhat better results and less variability than the plume height data from the FEPS model when compared to observed plume heights. As previously mentioned, in some cases in the northwestern US, modeled plume heights from the FEPS model were extremely high and well above the atmospheric boundary layer. In reality, it is unusual for a smoke plume to be injected above the boundary layer (Mazzoni et. al., 2004), suggesting that raw plume height values are less important than if smoke is injected within or above the boundary layer, especially downwind (as shown by the somewhat better results in the BlueSky-CMAQ comparison than the BlueSky-FEPS comparison).

There is an overall lack of information about the values that drive heat-release and plume-rise estimates. Existing plume height algorithms and dispersion models attempt to calculate plume rise based on a series of physical processes and emissions estimates. The limited variability in the observed plume height data suggests that a simple empirical model, or lookup table, may produce better estimates of plume height than existing algorithms that are process-based and rely on estimates of heat release from fires. Given the current state of information, it is possible that average, default region-specific plume height data may be more representative. For example, several years of data from satellite plume height observations could be analyzed and used to produce statistical models that better characterize regional plume height. These models could then be used to improve air quality model performance.

6. ACKNOWLEDGMENTS

This work was funded by a NASA Applied Sciences cooperative agreement. The authors wish to thank David Diner for providing guidance on the use of MISR plume height data.

7. REFERENCES

Breyfogle, Steve and S. A. Ferguson. 1996. User assessment of smoke-dispersion models for wildland biomass burning. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. PNW-GTR-379. 30 pp.

Briggs, G.A. 1969. Plume rise. Prepared for: Nuclear Safety Information, Oakridge, TN. U.S. Atomic Energy Commission, Division of Technical Information Springfield, VA: Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards: U.S. Dept. of Commerce.

Grell G.A., Dudhia J., and Stauffer D.R. (1994) A description of the fifth-generation Penn State/NCAR mesoscale model (MM5). Prepared by the National Center for Atmospheric Research, Boulder, CO, NCAR Technical Note-398.

Kahn R.A., Li W.-H., Moroney C., Diner D.J., Martonchik J.V., and Fishbein E. (2007) Aerosol source plume physical characteristics from space-based multiangle imaging. *J. Geophys. Res*. **112** (D11205), 1-20 (doi:10.1029/2006JD007647).

Larkin N.K., O'Neill S.M., Solomon R., Raffuse S., Strand T.M., Sullivan D.C., Krull C., Rorig M., Peterson J., and Ferguson S.A. (2009) The BlueSky smoke modeling framework. *Int. J. Wildland Fire* (accepted).

McNamara D.P., Stephens G., Ruminski M., and Kasheta T. (2004) The hazard mapping system (HMS)–NOAA's multi-sensor fire and smoke detection program using environmental satellites. Paper presented at the *13th Conference on Satellite Meteorology and Oceanography, Norfolk, VA, September 20-23*.

Nelson, D.L., Y. Chen, D.J. Diner, R.A. Kahn, and D. Mazzoni, 2008. Example applications of the MISRINteractive eXplorer (MINX) software tool to wildfire smoke plume applications. SPIE Proceedings.

Raffuse S., Chinkin L., Sullivan D., and Larkin N. (2006) Applications of a GIS-based fire emissions model, or BlueSky SMARTFIRE. Presentation at the *Third International Fire Ecology & Management Congress, San Diego, CA, November 18*, by Sonoma Technology, Inc. and U.S. Forest Service AirFire Team (STI-3041).

Westerling A.L., Hidalgo H.G., Cayan D.R, and Swetnam T.W. (2006) Warming and earlier spring increase western U.S. Forest Wildfire Activity*. Science*, **313**, 940. doi:10.1126/science.1128834

National Exposure Research Laboratory (1999) Science algorithms of the EPA Models-3 Community Multiscale Air Quality (CMAQ) modeling system. Report prepared by the National Exposure Research Laboratory, Research Triangle Park, NC, EPA/600/R-99/030 (peer reviewed), March.

Young S.A. and Vaughn M.A. (2009) The retrieval of profiles of particulate extinction from Cloud Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) data: Algorithm description. *J. Atmos. Oceanic Technol*. **26**, 1105-1119, (doi:10.1175/2008JTECHA1221.1).