Joint Fire Science Program

Fire Science Brief

RESEARCH SUPPORTING SOUND DECISIONS

Researchers are using a truck-mounted lidar to study the dynamics of smoke plumes from wildland fires. Credit: V. Kovalev.

Using Lidar to Validate and Strengthen a Long-range Smoke Transport Model for Air Quality Forecasting

Summary

Researchers have explored the potential and limitations of using lidar, the remote sensing instrument, to provide information on smoke plume dynamics and optical properties. They used a scanning lidar in the smoke-polluted atmospheres near wildfires and prescribed fires to measure the height, dynamics, and three-dimensional dispersion of smoke plumes and the temporal and spatial variations of the optical properties of the smoke particulates. The team has developed and refined a measurement methodology and data processing techniques for analysis of data collected from smoky atmospheres by lidar and auxiliary instruments within the smoke-polluted area. They developed, validated, and improved lidar algorithms and software and, through a continuing project, are still working toward the ultimate goal of using lidar to estimate the optical and microphysical characteristics of particulates in smoke plumes. This research would further automate, speed, and improve the development of air quality forecast systems for areas downwind of wildfires.

Key Findings

- The research team developed, implemented, and improved a practical and efficient ground-based lidar remote sensing methodology for real-time monitoring and characterization of smoke plumes from wildfires.
- Lidar is the most appropriate instrument for determining wildland fire smoke plume boundaries, top height, and dispersion, and changes in these parameters with time. The near-continuous three-dimensional smoke plume data generated using lidar are critical in validating and improving smoke dispersion models, which are integral components of air quality forecasting systems.
- With this project the researchers contributed to improving a nationwide air quality forecast model by increasing our understanding of plume dynamics and their role in long-range transport of smoke plumes.

Local and international concerns about wildfire smoke

Wei Min Hao's interest in air quality effects of wildfires was triggered by his long-term research on fire emissions as well as by an inquiry about a far-off, big-picture concern. Hao is Team Leader/Atmospheric Chemist with the Forest Service Rocky Mountain Research Station's Fire Sciences Laboratory.

In the late 1990s the smoky springtime air of Missoula, Montana, where Hao lives, was an often-discussed topic locally. He heard many theories of what was to blame—agricultural burning, prescribed fires in the Northwest or Canada, even smoke from as far away as China—but the real answer was unclear. So he set out to develop a nationwide air quality forecasting system for smoke dispersion and air quality downwind of large wildfires.

Simultaneously, former Vice President Al Gore's taskforce on global climate change asked Hao how much greenhouse gases were produced by biomass burning in Indonesia, but he couldn't provide an answer.

This puzzle led Hao to seek and obtain funding from Joint Fire Science Program (JFSP) to study long-range smoke transport using the Hysplit model, which was originally developed by the National Oceanic and Atmospheric Administration (NOAA). That work highlighted the importance of knowing how high into the atmosphere a wildfire smoke plume is injected if you want to determine where the smoke particles will end up. Thus was born the current project to use lidar to analyze smoke plume dynamics.

Smoke from the 2009 Kootenai Fire, Montana.
Credit: S.P. Baker.

Fire emits pollutants such as aldehydes and ketones that irritate the human airway, making people feel uncomfortable and possibly triggering asthmatic reactions in susceptible people. Heavy smoke from fires can also reduce visibility and may cause traffic accidents and airport closures. Scientists need more information about how smoke moves and dissipates from wildland fires to inform downwind smoke advisories. Smoke transport is an interstate and international issue because smoke crosses political boundaries and influences the atmosphere's chemical composition and earth's climate.

Lidar as a new tool for studying smoke dynamics

Lidar works on the same principle as radar, but uses light from a laser to detect and locate atmospheric structures, such as clouds and smoke plumes. The laser emits short light pulses into the targeted atmosphere. The atmospheric particulates and molecules scatter the light in all directions. The light scattered back 180 degrees from the beam is recorded by a lidar photoreceiver versus time. The backscattered signal is stronger from a smoke plume because it contains more particles to scatter the beam of light than adjacent clear air.

Hao's team used a truck-mounted scanning lidar that automatically and rapidly changes the searching direction through 180 degrees horizontally and 90 degrees vertically. "It can basically scan in any direction," says Hao. "It's portable and can move around and assemble quickly."

Vladimir Kovalev, research physical scientist with the Forest Service Rocky Mountain Research Station's Fire Sciences Laboratory (FSL), believes theirs may be the only truck-mounted lidar in use for this type of research. Kovalev is the lead scientist in charge of designing lidar experiments, developing a methodology for the lidar measurements, and analyzing and interpreting the results. He uses computer analysis to separate out which signal came from clear air and which from smoke and at what height. This allows him to determine the boundaries of smoke plumes.

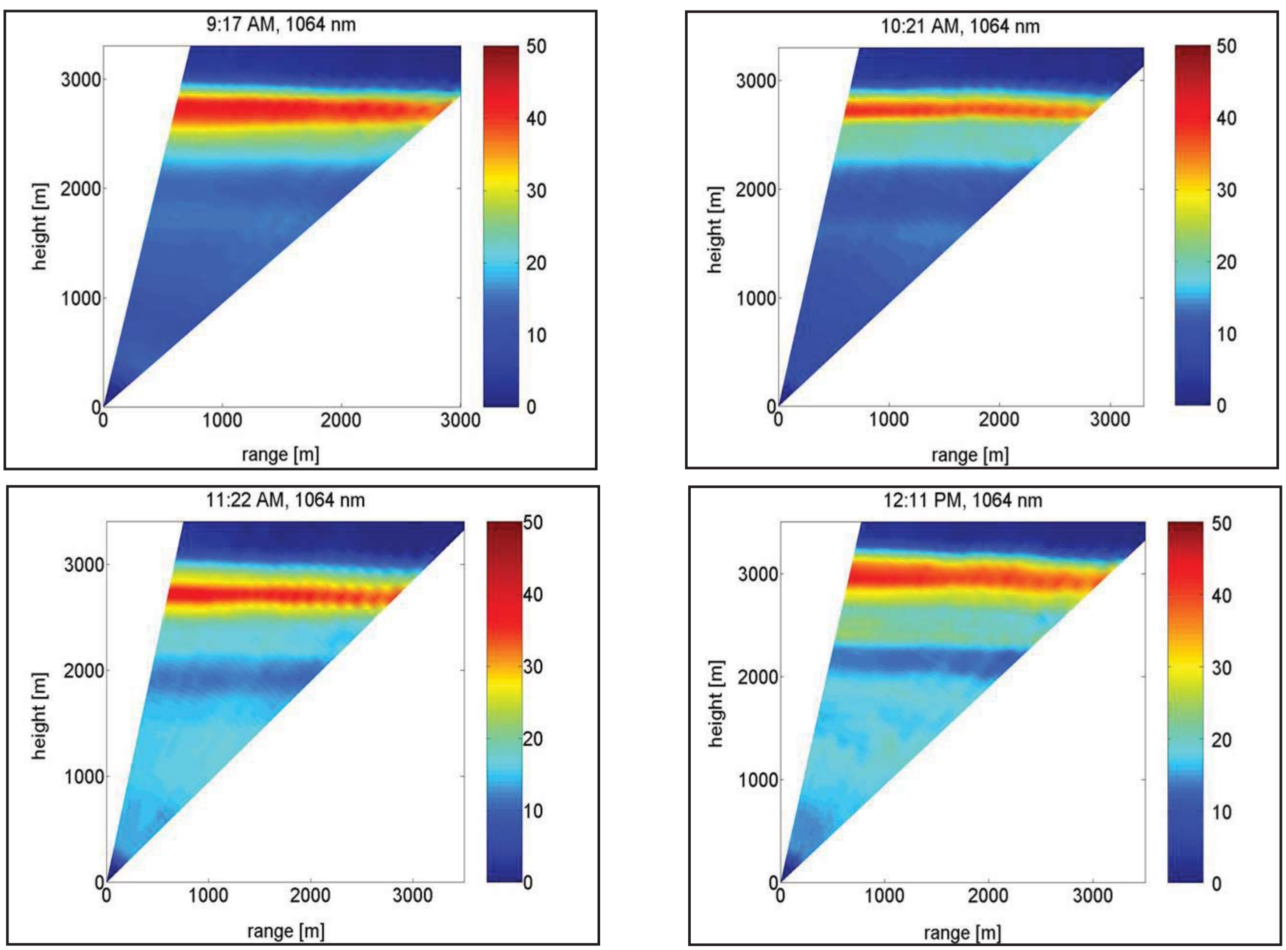
The FSL lidar gives a complete, three-dimensional view of the smoke plume up to 10 kilometers in the atmosphere. The truck-mounted lidar "provides critical information on plume heights and aerosol levels to validate smoke dispersion models," Hao says.

The mobile lidar setup. Credit: V. Kovalev.

The use of lidar allows for the first time ever real-time, continuous, high-precision remote measurement of the plume from the ground, Hao says. This is a distinct advantage over conventional plume monitoring instruments, which allow only point measurements.

Advantages and disadvantages of lidar and other plume monitoring tools

Smoke tends to disperse in layers, most often related to the time of day when the smoke was generated, but also to the kind of landscape and vegetation burned. Plume layering has generally been measured from an airplane, but that is extremely expensive. Planes of course have limited flight time, whereas the ground-based scanning lidar setup can monitor continuously for 24 hours or longer. Planes cannot operate in very rough weather, and their ability to fly near large wildfires is restricted for the safety of the pilot. An advantage of a plane over the lidar is that a plane can gather data on smoke plumes over a wide area, whereas lidar is effective only to distances about 10 kilometers from the measurement site. Hao's team used measurements made from planes to "validate their smoke plume model and to understand the photochemical reactions in the smoke plume," he says.



Examples of vertical lidar scans obtained over approximately 3 hours in the vicinity of the Montana I-90 Fire on August 12, 2005. The color scale shows the relative level of backscattering. The dark blue colors show clear-air areas, the green, yellow, and red colors show areas and layers polluted by smoke particulates. Note a significant transport of the smoke particulates down to heights below 2,000 meters in the two later figures. Credit: V. Kovalev.

Satellite imagery is also used for routine smoke plume monitoring, but this allows only after-the-fact analysis. Satellite analysis is limited by the location of the data receiving station and the frequency of satellite passes over the fire. Some researchers have recently begun to try to use lidar data from satellites shooting down to the earth.

Validating and improving plume-rise models

Three or four different plume-rise models exist. None had previously been validated with actual field-derived data. When Hao and Kovalev's group compared the models' results to the lidar measurements of actual wildfire smoke plumes, none of the models performed well. "So then we needed to do more lidar measurements to improve the plume-rise models," Hao says, because it's infeasible and too expensive to use lidar measurements for every fire. Some of the assumptions on which the models were built must have been inaccurate, but "training" them with real data from the lidar has and will improve their results.

The team's long-term goal in the next 4 years is to make the plume-rise model applicable to fires in different ecosystems throughout North America.

The team's long-term goal in the next 4 years is to make the plume-rise model applicable to fires in different ecosystems throughout North America. This will require Hao and Kovalev to gather and analyze more lidar data over a wider spatial area.

Plume height is key to forecasting

The key issue in forecasting plume transport is how high the plume shoots up. Plume height depends largely on the time of day and the weather conditions. Hao and Kovalev's team measured maximum plume heights of more than 26,500 feet, but the most heavily polluted layers typically occurred between about 6,500 and 10,000 feet. You need to know the plume height to forecast how the smoke will disperse.

Multiple contributions to a nationwide air quality forecasting effort

In 2004, Congress tasked several federal agencies led by NOAA with developing an air quality forecasting system. One of the systems is the Weather Research and Forecasting (WRF) model. The main WRF model addresses pollutants from sources such as automobiles, factories, power plants, and vegetation. The air quality forecast results are accessible to resource managers nationwide via a website.

Hao's team contributed to the WRF effort in various ways. Scientists at NOAA and the National Center for Atmospheric Research produced the WRF-Chem model, a component of the WRF model, to account for all of the above pollutants plus, through the contributions of Hao's research group, the effects of wildfires. Hao explains, "Our contribution to WRF-Chem was to quantify the emissions of pollutants and the greenhouse gases produced by wildland fires." This was a unique challenge because wildfire locations change everyday and vary spatially and temporally. "The fire is a wildcard," Hao continues. "You really don't know when and where it will happen."

Plumes from the 2006 Tripod Fire, Washington.
Credit: V. Kovalev.

This lidar study was an attempt to develop remote sensing–based methods of determining plume rise from wildfires for the air quality forecasting models. Remote sensing–based methods increase the accuracy, of air quality forecasting.

"If you want to do forecasting, you have to do it fast," says Hao. "If it takes too long to generate or process the data or run the model, then that defeats the purpose of forecasting. Everybody wants the information in real time," he continues. "If two weeks later you tell them what you know, it's too late, especially for the air quality managers. They want to know now—in the next 24 hours. Otherwise, they're not interested." It does nobody any good to know that two weeks ago their area was exposed to noxious smoke, and people could get upset at not having been forewarned of the dangers.

The team that Hao leads used the lidar data gathered through this project to improve the Weather Research and Forecasting-Smoke Dispersion (WRF-SD) model. WRF-SD is closely related to the much larger WRF-Chem effort. WRF-SD is now a prototype. The results of WRF-SD will plug into WRF-Chem once WRF-SD is completely validated and optimized through comparison to the actual field data on smoke plume dynamics gathered using lidar, airplane, and on-the-ground monitors.

In another part of the larger WRF effort, Hao's team examined and strengthened satellite fire detection techniques, which, along with plume rise studied here, is the other "variable of critical importance in determining the impact of fires on air pollution," Hao says. For additional information on satellite data-driven air quality forecasting from wildfires, see JFSP Brief 74, "Lookouts in the Sky with Algorithms," accessible at www.firescience.gov/projects/01-1-5-03/supdocs/01-1-5-03_fsbrief74-final.pdf.

Another view of plumes from the Tripod Fire.
Credit: V. Kovalev.

Quantifying the particles in the plume: An elusive goal

Kovalev and Hao are still working toward the as yet elusive goal of estimating mass concentration in smoke-polluted atmospheres using optical equipment. The current standard method involves collecting and weighing particulates on a filter. The researchers' goal is to mathematically relate the optical parameters, such as the optical depth and the extinction and backscatter coefficients of smoke derived from the lidar signals, to a more user-friendly unit, such as milligrams per cubic meter.

The use of lidar to characterize wildland smoke plumes is still in its infancy.

The use of lidar to characterize wildland smoke plumes is still in its infancy. Kovalev is refining the measurement and analysis techniques and software, and the team needs to gather additional data from fires in different locations and with different vegetation to test and improve the techniques developed through this project. It can be difficult to gather high quality data because fire behavior is unpredictable and smoke plumes often shift directions erratically. It can take a long time to find a "proper" wildfire for measurement, and it can be even more difficult to establish in good time the right place and the right time for the lidar measurement site.

An area of future research would be to "look at the different smoke plume layers near an urban area, say in California," Hao explains. "There you have plumes from automobile and industrial sources along with smoke plumes from the wildland fires. These plumes have different chemical compositions and aerosol concentrations. We need to refine the techniques for using lidar to separate these plumes."

Another possible future study would be to cooperate with another lidar research team, perhaps at the National Aeronautics and Space Administration (NASA), that has different types of lidar. This collaboration could further expand the volume of information about smoke plume characteristics.

Management Implications

- Lidar is a powerful instrument to measure smoke particulates in realtime.
- Lidar analysis of smoke plumes is instrumental in the development of more accurate air quality forecasting models. How the plume rises affects how it will travel, which is critical in determining downwind air quality and effects on public health and safety.
- Lidar analysis of wildfire smoke plumes contributes to our understanding of fire behavior. Lidar could be used to get an initial read about atmospheric conditions on an inaccessible remote fire.

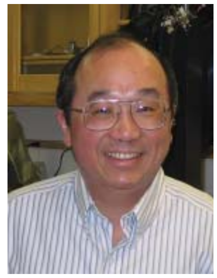
Further Information: Publications and Web Resources

Lidar: http://en.wikipedia.org/wiki/LIDAR

Optics.org, 2010. Lidar tracks forest-fire pollution. Jan. 11. http://optics.org/cws/article/research/41380

Scientist Profiles

Wei Min Hao is the Team Leader of the Fire Chemistry Group at the Fire Sciences Laboratory of the Rocky Mountain Research Station, USDA Forest Service, in Missoula, Montana. Dr. Hao's research interests are to understand the impact of fires on regional and global air quality and on global climate.



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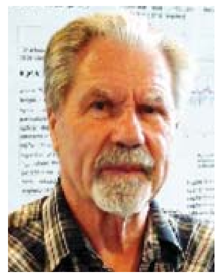
Vladimir Kovalev is a Research Physical Scientist for the Fire, Fuel, and Smoke Science Program at the Fire Sciences Laboratory of the Rocky Mountain Research Station, USDA Forest Service, in Missoula, Montana. His research focuses on the development and modification of methodologies and algorithms for processing data of the FSL lidar in smoke-polluted atmospheres, the supervision of lidar measurements, and data processing and analysis.



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