2009

# Lookouts in the Sky with Algorithms: Forecasting Air Quality with Satellite-sent Data

Lisa-Natalie Anjozian
*US Forest Service*, lisa@toeachhisownmedia.com

Joint Fire Science Program
Fire Science Brief
RESEARCH SUPPORTING SOUND DECISIONS

Lookouts in the sky watch for fire on earth. This photo shows the Biscuit Fire in Oregon taken on August 22, 2002 by National Aeronautics and Space Administration's (NASA's) New Satellite, Aqua. Credit: Jacques Descloitres, Moderate Resolution Imaging Spectroradiometer (MODIS) Land Rapid Response Team at NASA Goddard Space Flight Center.

# Lookouts in the Sky with Algorithms: Forecasting Air Quality with Satellite-sent Data


## Summary

Data and algorithms from earth-orbiting satellite observations provide key components in scientists' tools that can map active fires and burn scars. Fire perimeter maps can then be crafted using this data. Armed with fire perimeter maps that have been linked to fuel maps of the area burning, scientists can calculate emissions from recently burned areas, determine the quantity of emitted gases and particulates, and determine where these emissions will travel downwind from the burn site. For this project, data from satellite sources has been compared against data collected on the ground by ground-based instruments and incident management teams, and the algorithms validated.

Techniques, algorithms, and software, such as fire detections, burn scar detections, and emission maps—created or updated for this project—are generally applicable to any air quality forecasting system. Data and information will be made readily available to managers through a publicly available web site.

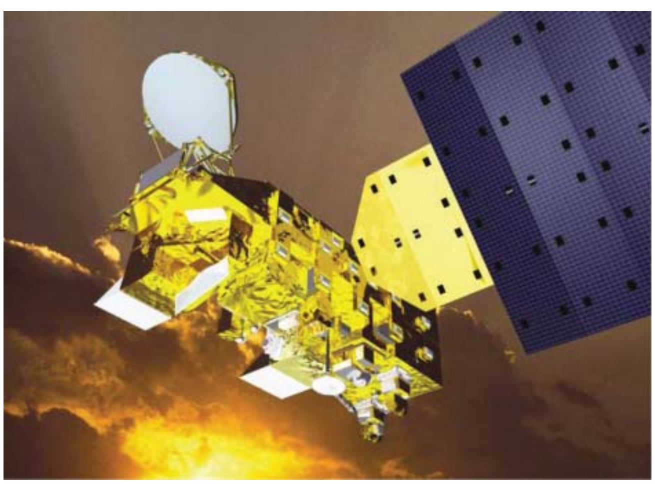
### *Key Findings*

- Algorithms to detect actively burning areas, and to detect areas that have burned between satellite passes were created and validated.
- Fire product and burned area product complemented each other, delivering information the other was incapable of delivering due to timing of observation, or frequency of observation.
- The Moderate Resolution Imaging Spectroradiometer (MODIS) fire product detects most of the fires.
- The team developed a fuel map for use with the First Order Fire Effects Model (FOFEM), in order to use FOFEM's default fuel loadings in the air quality forecasting system.

## Introduction

In the recent past, the job, before structures were built atop towers or mountains, required the lonely lookout to climb to the nearest ridge or peak after a thunderstorm, look for smoke, hike back down to the cabin, and telephone headquarters. Then, the lookout would have to grab gear and head out to fight the fire.

While watching for fires is older than our technologically complex era, our monitoring of this ancient phenomenon is still an incredibly recent undertaking. Fire predates the only species that can prevent, suppress, assess and manage it. We are continually reworking our relationship to fire, learning to live and coexist with fire. At the same time we strive to improve the way we get a handle on what fire is up to, where it is lurking, where it is bolting. Our farthest lookouts, set with the task of detecting fires, are orbiting above us—equipped with cameras and math—to relay data and equations so scientists can craft the answers. Wei Min Hao, Team Leader/Atmospheric Chemist with the Forest Service Rocky Mountain Research Station's Fire Sciences Laboratory, along with his team, has produced techniques, algorithms and software for fire managers to use to get a handle on fire's effects.



A computer rendering of the Aqua satellite spacecraft done by Reto Stöckli, based on earlier versions. This satellite is part of NASA's Earth Observing System, that delivers data on fires actively burning and areas recently burned through the onboard MODIS instruments. Credit: http://aqua.nasa.gov/doc/pubs/Aqua_brochure.pdf, Aqua brochure.

## Beyond the traditional lookout, with a greater range of vision

Centuries ago, the poet Robert Browning mused, "Ah, but a man's reach should exceed his grasp, Or what's a heaven for?" As a species, our reach has certainly exceeded our grasp. Far above our revolving world, the satellites we have placed in space perform observations for us. The Terra and Aqua satellites, part of NASA's Earth Observing System (EOS), give Hao and his team the ability to track fires, in almost real-time, to see where fires are, and how they grow. Flying aboard each of these satellites is MODIS (Moderate-resolution Imaging Spectroradiometer), an instrument laboring as the modern lookout. Sweeping through space, watching earth in a 1,450-mile swath, MODIS sees the entire earth every 1–2 days—every point on our planet. As the satellites fly in low earth orbit—only 440 miles above the ground that fire teams cover on foot—and travel from pole to pole, the MODIS on Terra sees the earth during the morning, and the MODIS on Aqua sees the earth in the afternoon.

When the satellites are near, Hao and his team's instruments look up—and collect data, as much as twelve times in a day. Comparing what they learn from space with what they learn from instruments based on the ground, and from fire incident managers' reports, Hao's team is able to study the impact of fires on air quality, and to offer an automated system that can forecast where smoke will go, and predict air quality across the continental United States.

## The motivation

There was no systematic method of compiling fire data nationwide and presenting it in a coherent way with a short delay until the early 2000s. The daily intelligence on fire locations and burned areas was compiled from ground surveys conducted by individual Geographic Area Coordination (GAC) centers; the information was reported the next day.

In 2001, Hao decided to develop a nationwide system to monitor in near real-time the distribution of active fires throughout space (across the land) and time, fire severity, burned areas, and smoke dispersions using the latest satellite remote sensing technology. A nationwide fire monitoring system compiles and disseminates updated information on the extent of fires over a large region. The information is critical for the GAC's success in formulating daily firefighting strategies, resource allocation, and predicting air quality. Air polluted by smoke can violate Environmental Protection Agency's ambient air quality standards, reduce visibility, cause traffic accidents and airport closures, affect public health, and influence regional and global climate.

Smoke can cause highway safety problems when it impedes a driver's ability to safely see the roadway. Credit: Jim Brenner, Forest Service; image found in *Wildland Fire in Ecosystems Effects of Fire on Air*.

## Job description for a twenty-first century lookout

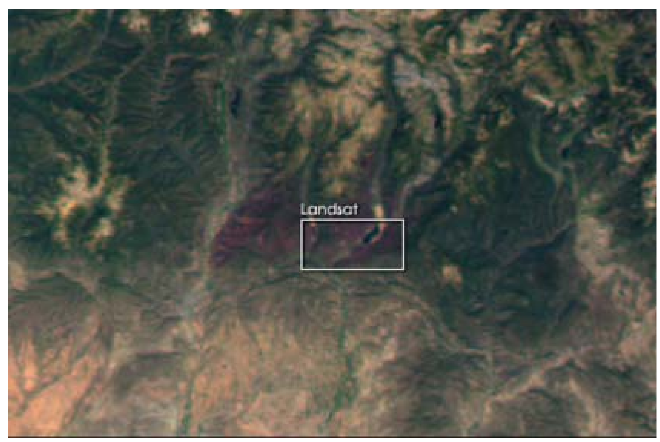
Like any tactical plans managers use to coordinate fire personnel, the air quality forecasting system designed by Hao's team employs each component in a sequence: MODIS flies over, aboard the satellites. MODIS delivers two components, the MODIS Fire Product and MODIS Burned Area Product. These two go into delivering a third component, the MODIS Fire Perimeter. All of these components operate on the data the satellites see and provide as they acquire it. On the ground, a satellite receiving station retrieves, decodes and processes the MODIS data. Four times a day, the individual MODIS observations are collected into a national fire perimeter data set. After this collection takes place, all of the system components work continuously, which is not tightly linked to the particular times the satellites first acquired the data.

The system designed by Hao's team can then provide answers about the type and quantity of pollutant emissions resulting from a burning landscape, and predict where smoke will travel using the photochemical transport/transformation product. Managers can then inform the public about expected air quality problems in different regions. Like the rain gauges, instruments, and wind velocity blades that collect data near Civilian Conservation Corp-era constructed lookouts, each component of Hao's system delivers a piece of information that allows the forecasting system to provide the most accurate scenario possible.

### *MODIS fire, burn scar and fire perimeter products*

The MODIS fire and thermal anomalies products can deliver—whether it is day or night—information about when fire occurs, where it is occurring on the landscape, and how much energy a fire is emitting. The MODIS burned area product uses an algorithm that can tell the approximate date an area burned, and map the placement and extent of recent fires, distinguishing from fires that occurred months or years prior. The burned area product can also indicate gaps in the information it supplies, whether owing to missing or poor quality data. While these products use algorithms that have passed scrutiny through simulations by scientists, and have been continually improved, Hao's team delivered the first validation of these tools' ability to predict fire areas by comparing information the products delivered with information on specific large fires gathered on the ground by fire incident management teams.

In testing the MODIS fire product, Hao's team found that some areas actively burning on a major fire were not detected, even areas that the incident management team on the ground had reported. "The shortcomings of this method do not appear to be associated with the physics of the fire detection algorithm itself," Hao offers, "but rather with the sampling frequency associated with a polar-orbiting satellite." The team further compared the fire detection algorithm to a database of different agencies' fire reports. The validation demonstrated that the MODIS fire detection algorithm detects the majority of fires over 2,470 acres in size.




The burn scar of the Missionary Ridge fire appears dark red. in this MODIS image from August 10, 2002. Credit: Robert Simmon and Jesse Allen, NASA Goddard Space Flight Center; image found at http://earthobservatory.nasa.gov/Features/BAER/printall.php.

While burned area products already existed, Hao's team developed a burned area product that needs only one image, as opposed to two cloud-free images. It can also penetrate thin layers of smoke. The burned area product developed by Hao's team is a critical component of the air quality forecasting system. Since the fire product algorithm can only detect what is burning at the time either satellite-based MODIS instrument is passing over during a fire, the ability for scientists to detect and process area that has burned between satellite observations is vital. Scientists need this information to determine whether the fire MODIS is seeing in two sequential observations is a flaming front advancing, or a new fire starting. The burned area product can also tell scientists about the interior space of the fire perimeter. "Are the gaps unburned islands or did they burn between MODIS observations?" Hao asks. One of the equations the scientists tested delivered false alarms in reporting fire, confusing water, cloud shadows and clouds over water with burned areas. Hao's team tested and validated the best equations to deliver the most accurate reports on a variety of conditions.

Because the burned area product can deliver fire information that the satellites didn't see while flying through the sky, scientists can infer fire activity from burn scar detections. While variations in the fire product information can result from gaps in the satellites' timing of observations, variations in the burned product information can result from obscuring smoke and clouds. Though the burn scar algorithm can penetrate some smoke, it needs heavy smoke to disperse before it can give reliable burned area detections. The fire product and burned area product complement each other, delivering what the other can't because of their timing or properties of their wavelengths. These two products are combined to deliver near real-time fire growth in a landscape through the MODIS fire perimeter.

## Where there's fire, there's smoke

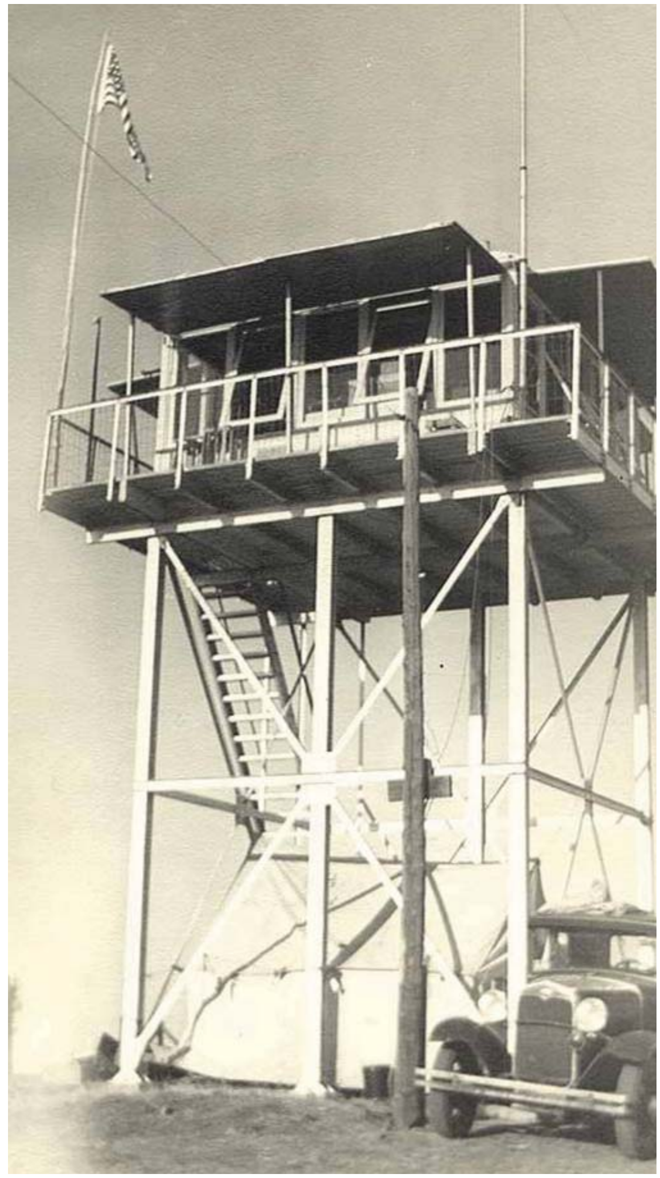
Scientists need information on four basic elements to calculate emissions:  area burned, fuel loadings, fuel moisture and emission factors. Because smoke not only gets in our eyes, as the song goes, it also gets in our lungs, knowing where smoke will go and how air quality will be affected is important to the public.

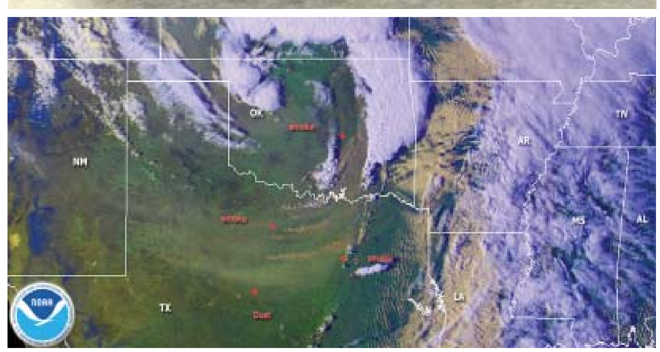
### *Emissions from fire and transport/ transformation components*

With the fire area information provided by the MODIS products, and a map of the fuels found in the landscape that is burning, the scientists can calculate the emissions produced from the fire. Hao's team offers that their method is not limited to using satellite observations, but can also use simulated information from a fire behavior model FARSITE. "The first step to calculate emissions for a burning period is to compute the new area burned in that period," Hao says. "The second critical component of an emissions calculation is knowledge of the fuel loadings. Our system uses the fuels loadings provided by the First Order Fire Effects Model (FOFEM) software."

Hao's team developed a fuel map directly linked to FOFEM default fuel loadings. The map uses the nationwide Fuel Characteristic Classification System (FCCS) fuelbed map as a source. Lastly, knowledge of the specific emission factor of a compound to apply to the fuel type is essential. The emission factor is defined as the amount of a compound emitted per kilogram of biomass burned. Through their research, Hao's team found only a few significant categories of emission factors—forest, grass, and shrub.

To make forecasts, the scientists select the appropriate emission factor based on the general ground cover category





On the watch for smoke and fire—personnel, machines, and math. (Top) Vintage photo of the Miami Mountain Lookout, 1945. Credit: U.S. Forest Service, found at http://www.fire-lookouts.org/index.htm. (Bottom) An April 2009 National Oceanic and Atmospheric Administration (NOAA) Operational Significant Event Imagery (OSEI) satellite image showing dense smoke from wildfires in north central Texas, southern and central Oklahoma combined with blowing dust from the region. Credit: NOAA, found at http://www.osei.noaa.gov/Events/Fires.

found in the fire area, and combine this with the other necessary elements to run calculations using the FOFEM program. The special version of FOFEM they developed, which runs on Linux, then delivers a set of emissions maps of the burning period for the contiguous United States. To serve their particular needs, managers could format the maps to give emissions by fire event, by state, by region, by nation, or by total emissions. Each map gives emissions calculations for a particular chemical tracked by the system.

With the components assembled, computations produced, maps developed, the scientists can deliver near real-time smoke transport information through their Weather Research and Forecasting (WRF)-Smoke Emissions and Dispersion Team. Using WRF, Hao's team can predict, for a 12–36 hour forecast period, how fire will behave, and where and what quantity of particulates and gases will travel downwind from a large fire. The techniques the team developed, Hao offers, can be used by other air quality forecasting systems that use MODIS-relayed, real-time information. The template for a generic air quality forecasting system the team created can also use data from other satellite-based instruments. While the flat disk covered with a topographic map of the 360º landscape and fitted with the movable sight, known as the Osborne Fire Finder, is still being used by those on the watch for fire at mountaintop lookouts—the twenty-first century tools developed by Hao's team give fire personnel additional resources.

While the basic information provided through the sight and speech of lookouts is still vital in reporting and tracking fires, the silent service of math and space age machine adds a valuable expansion to our reach, to offer others our briefest warning, "Fire!"

*...the silent service of math and space age machine adds a valuable expansion to our reach...*

## Further Information: Publications and Web Resources


Hao, W.M., J.M. Salmon, B.L. Nordgren, Y.J. Kaufman, and R.-R. Li. 2003. Daily emissions of CO and $PM_{2.5}$ from a large fire in the U.S. using MODIS data, in *Proceedings of ILEAPS: Integrated Land Ecosystem–Atmosphere Processes Study*, vol. 1, edited by A. Arneth, H. Korhonen, M. Kulmala, M. Raivonen, T. Ruuskanen, and T. Suni, Helsinki, Finland, 130-133.

Hao, W.M., D.E. Ward, R.A. Susott, R.E. Babbitt, B.L. Nordgren, Y.J. Kaufman, B.N. Holben, and D.M. Giles. 2005. Comparison of aerosol optical thickness measurements by MODIS, AERONET sun photometers, and Forest Service handheld sun photometers in southern Africa during the SAFARI 2000 campaign, *Int. J. Remote Sensing*, 26 (19), 4169-4183.


### Management Implications

- Managers can see, through the MODIS fire perimeter generated maps, if two or more fires have merged into one.
- Managers have access to daily emissions maps with a 1 kilometer by 1 kilometer spatial resolution for the contiguous United States.
- Managers can format maps to give emissions by fire event, by state, by region, by nation, or by total emissions. They can also obtain emissions calculations for a particular chemical.


Kaufman, Y.J., C. Ichoku, L. Giglio, S. Korontzi, D.A. Chu, W.M. Hao, R.-R. Li, and C.O. Justice, Fire and smoke observed from the Earth Observing System MODIS instrument—products, validation, and operational use, *Int. J. Remote Sensing*, 24, 1765-1781, 2003.

Li, R.-R., Y.J. Kaufman, W.M. Hao, J.M. Salmon, and B.-C. Gao, A technique for detecting burn scars using MODIS data, *IEEE Trans Geosci. Remote Sensing*, 42 (6), 1300-1308, 2004.

## *Scientist Profile*

**Wei Min Hao** is the Team Leader of the Fire Chemistry Group at the Fire Sciences Laboratory of the Rocky Mountain Research Station, U.S. 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.

*Wei Min Hao* can be reached at:
RMRS Fire Sciences Laboratory
5775 US Highway 10 West
Missoula, MT 59803
Phone: 406-329-4838
Email: whao@fs.fed.us

## *Collaborators*

**(Late) Dr. Yoram Kaufman**, Senior Scientist, NASA Goddard Space Center
**Dr. Bruce B. Hicks**, NOAA/OAR Air Resources Laboratory

*Results presented in JFSP Final Reports may not have been peer-reviewed and should be interpreted as tentative until published in a peer-reviewed source.*

***The information in this Brief is written from JFSP Project Number 01-1-5-03, which is available at www.firescience.gov.***

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John Cissel
Program Manager
208-387-5349
National Interagency Fire Center
3833 S. Development Ave.
Boise, ID 83705-5354

Tim Swedberg
Communication Director
*Timothy_Swedberg@nifc.blm.gov*
208-387-5865

Writer
Lisa-Natalie Anjozian
*lisa@toeachhisownmedia.com*

Design and Layout
RED, Inc. Communications
*red@redinc.com*
208-528-0051