# BIOMASS BURNING

## Observations, Modeling, and Data Assimilation

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Fires affect the Earth system in multiple ways. They are a major source of aerosol particles, greenhouse gases, and other trace constituents in the atmosphere (Crutzen and Andreae 1990; Seiler and Crutzen 1980). They alter the exchanges of matter and energy between the land surface and the atmosphere, with important implications for local, regional, and global environmental patterns. Moreover, fires play a significant role in affecting air quality, the ecosystem, land use, public health, and safety.

To understand the role of fires in changing climate conditions and socioeconomic landscapes, recent scientific studies of biomass burning have focused on two goals: i) quantifying the emissions of aerosol particles and trace gases from fires and improving the description of spatial and temporal patterns at mesoscale or finer resolutions and ii) characterizing and understanding the effect of these emissions on atmospheric processes at various scales, ranging from human health and air quality impacts at a local scale to cloud properties and precipitation at a regional scale to interactions with Earth's climate on a decadal scale.

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### NCAR ECSA JUNIOR FACULTY FORUM ON FUTURE SCIENTIFIC DIRECTIONS 2010: BIOMASS BURNING

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| WHAT: | Junior faculty with diverse backgrounds in the physical sciences met with senior scientists in the field of biomass burning to discuss current science and near-term research problems in the study of fire emissions. |
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| WHERE: | Boulder, Colorado |

The last decade has seen significant progress toward both goals. Estimates of fire emissions have been greatly improved by better, more comprehensive satellite observations. Global emission inventories are now routinely updated, some in near–real time, with the spatial resolution on the order of kilometers to tens of kilometers and temporal sampling on the order of hourly to a few days (e.g., Reid et al. 2009; van der Werf et al. 2010). Equally dramatic advances have been made in the numerical simulation of the transport and evolution of smoke-related species, which feature both higher resolution and improved descriptions of relevant dynamic and chemical processes. These scientific advances have also benefited from rapid growth in computational power, extensive and detailed laboratory experiments, improved access to ground-based observation networks, and numerous intensive field campaigns. This richness of observations, combined with improvements in atmospheric simulations, has driven broad-based research programs at institutions around the globe aimed at understanding the role of fire in the Earth system. However, large uncertainties remain in our description of the magnitude, patterns, and drivers of biomass burning and the effects of burning emissions on weather, climate, and human health.

The Junior Faculty Forum on biomass burning was convened in July in Boulder, Colorado, to bring active young scientists from diverse backgrounds, ranging from ecology to meteorology to chemistry, together with recognized senior experts in simulation and observation of fires and smoke. This group was charged with evaluating the state of biomass-burning research, including nascent and emerging research directions, and discussing potential near-term collaborations as well as possibilities for breakthroughs in this field in the medium term. What follows is a brief overview of the topics discussed at the forum; for additional details, including complete presentations given at the forum as well as lists of the forum participants and invited speakers, please see the Junior Faculty Forum online (at http://wiki.ucar.edu/display/jff/Biomass+Burning).

**RECENT ADVANCES.** *Observations of fires and estimates of smoke emissions.* The basic information about the prevalence and spatio temporal patterns of fires is the foundation of any attempt to understand the role that fires play in the dynamics of land and atmosphere at landscape, regional, and global scales. Databases of fire activity spanning multiple decades are now available for Canada, Alaska, and the continental United States. Fire products for global studies have been produced from several different satellite sources. Fire products from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Kaufman et al. 2003) are the basis for decade-long, consistently processed records of both burned area and active fires. With these datasets, the basic decadal trends and interannual variability of fires in every region of the globe have been described.

Extraction of additional information from satellite data, beyond the location and timing of fires, has also been an area of rapid development. Active fire detection data from MODIS and the National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite (GOES) now include fire radiative power (FRP), an estimate of the energy release associated with fire for each pixel. This energy release has been shown to relate directly to the rate of fuel consumption in fires. A complementary approach has used high-spatial-resolution data from Landsat and similar satellites to estimate the severity of burns, which can then be linked to the level of fuel consumption.

New datasets have been developed to address specific kinds of environmentally significant fire activity, such as agricultural fires and peatland burning. The importance of subsurface carbon reservoirs in the global carbon cycle has placed a spotlight on peatlands, where large amounts of fossil carbon are now subject to burning because of changes in climate and human land use practices. The role of fire in agricultural practices, as well as land cover and land use change, has been subject to scientific and political scrutiny for its relevance to environmental quality and resource management.

Atmospheric observations at scales ranging from measurements of trace gas species and particles in fresh smoke plumes to global records of background trace gas concentrations are now available. Measurements of the chemical composition and emission factors of smoke produced by different fuels under a variety of burning conditions have been made both in the field and in the laboratory. New and improved techniques, such as airborne Fourier transform infrared spectroscopy (FTIR), have made possible the measurement of a much wider range of chemical species in smoke.

At a broader scale, satellites now produce global records of the chemical composition of the atmosphere. Plumes from large burning events have been tracked across the globe using aerosol and trace gas retrievals from many different instruments. These data have also been used to quantify the contribution of biomass burning to regional and interannual variations in atmospheric composition.

Information on smoke composition and records of fire activity have been integrated to create spatially and temporally explicit estimates of biomass-burning emissions. Several multiyear global inventories have now been produced, using different methodologies and different inputs. These "bottom up" inventories provide the basis for detailed analysis of the atmospheric effects of fires, particularly as emission inputs to regional and global models of atmospheric constituent transport and chemistry.

*Atmospheric simulation of smoke effects.* High-resolution simulations of fire behavior at 100-m-length scales have shed light on the complex dynamics in the immediate vicinity of fires, and the feedbacks of these dynamics on finescale meteorology. Model outputs are used for the estimation of smoke radiative forcing at the top of the atmosphere, within the atmosphere, and at the surface. Smoke has different effects in different layers of the atmosphere: absorption of smoke particles heats the atmosphere; however, the radiative extinction of a smoke layer generally reduces the solar input at the surface, cooling the surface.

Simulations of smoke transport and interaction with clouds have shown intriguing covariances between cloud properties and smoke intrusion. Cloud microphysical models simulating the response of cloud properties to aerosol size, concentration, and composition are being used to build a more complete representation of smoke–cloud interactions.

State-of-the-art weather models have started to incorporate direct, indirect, and semidirect effects of smoke aerosol emissions. Simulations of direct radiative impacts of smoke and feedbacks to meteorology, such as the smoke semidirect effect, are now incorporated as standard modules in some weather forecast models. Smoke emissions data are fed into atmospheric models to analyze the 3D distribution of aerosols and visibility, with some products available in near–real time for forecasting applications.

*Integration of model and observational data on fire.* Inverse methods and data assimilation techniques are becoming useful in estimating emissions based on observations of the atmospheric composition downwind of these fires. This is largely facilitated by the availability of satellite observations (e.g., carbon monoxide, aerosol optical depth, oxides of nitrogen, and ozone), which provide a larger "global" context of these events. "Top down" emission estimates are derived from statistically weighted comparisons between simulated and observed concentrations of constituents in the smoke plumes transported away from the fires. This approach provides a systematic means to evaluate and understand the accuracy of the bottom-up inventories currently used as input in chemical transport models (CTMs). To date, the validation of these inventories has been carried out either through dedicated field campaigns [such as the Southern African Fire–Atmosphere Research Initiative (SAFARI)] or through indirect comparisons with smoke observations. Results from inverse modeling experiments provided top-down constraints on the magnitude and seasonality of fire emissions, and have highlighted persistent discrepancies in the bottom–up inventories.

**NEAR-TERM SCIENTIFIC DIRECTIONS.** The participants and invited speakers at the forum are all presently engaged in active ongoing research on science questions involving biomass burning. Many of the presentations included well-formed, actionable follow-up experiments, and during the discussions, the group agreed that several of these were not only worthwhile science but also community priorities for improving our understanding of the role of fire in the Earth system.

Despite advances in observational inputs, daunting uncertainties in emissions estimates persist, with integer factor differences between different inventories and between bottom-up and top-down estimates. There are several reasons for these uncertainties, including the following:

- Fires are highly variable, and much of this variation is at scales finer than the resolution of current observations. This means that despite the volume of observations available, many important aspects of fire behavior must still be parameterized in models.
- The full set of observations relevant to characterizing fires spans a wide range of observation types and disciplines. Models of fire behavior have not yet integrated this full range of relevant observations.
- Use of downwind observations to constrain emissions introduces uncertainties associated with the model representation of a range of phenomena, from dynamics to chemistry. These uncertainties need to be better understood to make the best use of inverse methods.

The forum participants identified a number of near-term research objectives that speak to the common goals of the Earth system science community. The scientific directions for observational, theoretical, and simulation studies as discussed at the meeting are described in the following sections.

*Remote sensing of fires.* While the characterization of the primary observations of fires used in large-scale fire inventories has improved, several key questions remain. The global datasets produced to date have relied on polar-orbiting satellites with a sun-synchronous orbit, meaning that all observations are taken at the same local time. Variations in fire detection caused by the sampling pattern of the available sensors, the viewing geometry, and the diurnal cycle of fire need to be better characterized to allow for the integration of fire information from multiple sensors. This effort will require the use of multiple high-resolution sensors. Airborne sensors provide the highest-resolution information; however, spaceborne sensors, especially the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on board NASA's *Terra* satellite, as well as Landsat, are valuable for statistical studies requiring large data volumes. This effort will also require the use of the ground-based fire information systems that exist for many of the fire-prone regions of the globe; these datasets are often complex to use, but they have a richness and detail that must be exploited to extract the most information from space-based observations.

As our scientific understanding of sensors currently in use improves, this knowledge must be applied to emerging sensors, especially geostationary sensors that will extend geostationary fire detection with frequently repeated observations to nearly all tropical land areas. Long-term fire data records spanning multiple decades and satellite platforms pose considerable challenges of consistency and accuracy, but they could become a key resource for a wide range of studies on the atmospheric and land surface effects of fires. In regions where long-term ground-based observation data exist, the ground and satellite data should be used together to combine the systematic consistency of space-based observations with the richness of detail supplied by ground-based observations.

The potential of directly quantifying the energy release of a fire (FRP) using satellite observations has been demonstrated in field campaigns and limited satellite experiments. The signal-to-noise ratio of FRP measurements must be quantified, as this determines the spatial and temporal scales at which this information can be used to quantify fire behavior. Furthermore, FRP retrieval alone may be insufficient for various needs, including estimates of fire temperature and fire size, which are important parameters for studying fire dynamics, fire weather, and the injection height of the smoke plume. New or improved methods to retrieve subpixel fire information are necessary to drive models of broad-scale fire behavior.

*Fire–weather interaction.* Weather is an important determinant of fire behavior, and the effect of weather on fire incidence and growth is extremely well studied in temperate and boreal ecosystems, especially in North America. This systematic work needs to be adapted to models using meteorological outputs from conventional numerical weather prediction (NWP) models, which generally do not include all the variables measured at fire-oriented weather stations. Fire–weather relationships also need to be developed and tested for other parts of the globe, especially the tropics. Capturing these relationships will yield the greatest improvement in descriptions of fires for forecasting applications.

*Modeling and parameterization of smoke plumes.* The dynamics and chemistry of fire plume development occur at a scale finer than current global and mesoscale NWP modeling, and so most models rely on simple parameterization. The last few years have seen important classes of systematic observations of plumes become available. These observations need to be integrated with finescale physical modeling of plume behavior. These studies are needed to refine statistical treatments used in coarse-scale models, to account for sampling biases in plume observations (satellite overpass limitations, large-fire bias), and to pave the way for the integration of physical treatments of plume development in transport models.

*Smoke–cloud interaction.* Interactions of smoke and clouds have received intense scientific scrutiny for decades, but these remain one of the key uncertainties in the radiative forcing of the atmosphere and a limitation in the predictions of future climate change. Studies of smoke–cloud interactions need to carefully consider the meteorological differences between clean and polluted cases in the same regions, to more effectively isolate the impact of smoke on cloud properties and precipitation.

*Chemical composition of smoke.* Beyond quantifying fire behavior, the data scientists rely on for partitioning emissions into various trace gas species and particle types are very sparse. The full benefits of improved maps of fuel characteristics will not be realized unless better measurements of emissions factors for those fuels become available. Multiple measurements in specific conditions could also open the door to an improved understanding of the factors governing species partitioning in smoke, eventually leading to better physical models of emissions.

*Characterization of emission inventories.* Global- and regional-scale transport experiments have shown that current emissions inventories do not reproduce the magnitudes of downwind pollutants very well. The two species that have the densest measurements and the strongest signal of burning emissions are carbon monoxide and aerosol particles, and the results with these two species tell a very different story regarding emissions uncertainties. Modeling experiments that incorporate multiple species are needed with fully paired analyses and comparisons with downwind observations of these species. This permits a consistency check and a diagnosis of biases in the species partitioning of emissions, the sink terms employed in the models, the biases in the trace gas and aerosol measurements, and numerous other factors that cannot be diagnosed in single-species experiments. Characterizing errors in both model and observations is critical. In addition, the evaluation of sink terms is an area where results from studies of biomass-burning emissions could be useful to the atmospheric chemistry community at large.

*Inverse modeling experiments.* More regionally focused experiments are needed to exploit the finescale spatial and temporal patterns observed in biomass-burning plumes. This type of experiment will provide opportunities to understand the differences in fire emission characteristics across different ecosystems and land use practices. In addition, more sophisticated experiments are needed to specifically evaluate hypotheses of fire behavior, such as the changes in fire behavior over the progressively drier conditions of a prolonged drought. Tighter collaboration between teams working on emissions inventories and teams doing atmospheric simulations must be pursued to reduce current uncertainties.

**OUTLOOK FOR THE FUTURE STUDY OF BIOMASS BURNING.** In a decade, the models used to simulate and predict biomass burning and its atmospheric effects may look very different from what we use today. It is possible to envision an integrated modeling system (e.g., weather–fire behavior models coupled with improved online atmospheric chemistry and transport models) that replaces many of the currently used statistical and parameterized treatments. Ignitions would be treated with a mechanistic integration of fuel conditions and data, such as lightning strikes and road traffic. Fire spread would be simulated by a high-resolution model representing the vegetation and the terrain, constrained by frequent observations of burning from space and airborne platforms. The partition of smoke emissions would be described by an emissions factors model that captures variations in emissions as a function of fuel composition, structure, and burning conditions. Plume development would be calculated with the same principles as convective development modified for additional heat and changes in composition associated with the fires.

Although components of such a system exist, a validated, real-time coupled system linking weather, fire behavior, and the evolution of chemical and aerosol species emitted from fires is beyond our current capabilities. Where observations exist, major computational challenges must still be overcome in modeling in real time the evolution of hundreds of constituents. Most of all, we must improve our understanding of the complexity and variability of fire behavior and fire emissions. This begins with a more complete understanding and reconciliation of the observations we already have across multiple scales. Likewise, fully coupled models cannot be run for all fires. To meet the goal of a global representation of fire emissions, models of fire behavior coupled to weather and chemistry must lead to theoretical understanding that can be scaled up to regional and global models.

The study of fire is scientifically compelling not only because it is an important process contributing to atmospheric composition and climate change but also because fire has so many direct effects on human life, from the destruction of property by wildfires to the effects on local and regional air quality of both wildfires and prescribed fires to broader questions of the role of fire in land and air resource management. The group assembled for this forum takes seriously their obligation to see the results of their scientific research passed forward as quickly as possible into the community for application to these pressing problems. It is our hope and expectation that the scientific study of fires and smoke will be productive for years to come, improving our understanding of the Earth system as well as the quality of our lives on the planet.

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