FOR SUBMISSION TO BAMS FOR PUBLICATION IN "MEETING REPORTS"

DRAFT 10 February 2011

BIOMASS BURNING – OBSERVATIONS, MODELING, AND DATA ASSIMILATION

NCAR JUNIOR FACULTY FORUM, 13-15 JULY 2010

EDWARD HYER, JUN WANG, AND AVELINO ARELLANO

AFFILIATIONS

1. HYER - Marine Meteorology Division, Naval Research Laboratory
2. WANG - Department of Earth and Atmospheric Sciences, University of Nebraska
3. ARELLANO - Department of Atmospheric Sciences, University of Arizona

CORRESPONDING AUTHOR

Edward J. Hyer, Naval Research Laboratory, 7 Grace Hopper Avenue, Monterey, California 93943

Email: edward.hyer@nrlmry.navy.mil

WHAT

Junior faculty and senior scientists met to discuss current science and near-term research problems in the study of fire emissions.

WHEN

13-15 July 2010

WHERE

NCAR, Boulder, Colorado

PARTICIPANTS

Avelino Arellano – NCAR/U. Arizona
Evan Ellicott – U. of Maryland
Edward Hyer – UCAR/NRL
Jessica McCarty – U. of Louisville
David Peterson – U. Nebraska
Mariya Petrenko – Purdue University
Markus Petters – North Carolina State
Gabriele Pfister - NCAR
Roberto Rivera – U. Central de Venezuela
Wilfrid Schroeder – U. of Maryland
Armin Sorooshian – U. Arizona
Daniel Tong - NOAA
Maria Val Martin – Barcelona Supercomputing Center
Jun Wang – U. Nebraska
Xiaoyang Zhang – NOAA NESDIS

INVITED SPEAKERS

Mian Chin – NASA GSFC
Janice Coen - NCAR
Charles Ichoku – NASA GSFC
Tom Moore – Western Regional Air Partnership
Jim Randerson – UC Irvine
Jeff Reid – Naval Research Laboratory

INTRODUCTION

Fires affect the Earth System in multiple ways. Fire emissions are a major source of atmospheric aerosol particles, CO_2, and other trace gases, and hence are a determinant of the observed patterns of atmospheric composition (Crutzen and Andreae 1990; Seiler and Crutzen 1980). Wildfires and anthropogenic fires (often associated with land conversion and farming practice) alter the exchanges of matter and energy at the land surface, and these changes can modify regional and global climate, raising the possibility of important feedbacks between climate and fires.

To understand the role of fires in changing climate conditions and socio-economic landscapes, recent scientific studies of biomass burning have focused on the following two goals: (i) to quantify the emissions of aerosol particles and trace gases from fires, including description of spatial and temporal patterns at mesoscale or finer resolutions; (ii) to characterize and understand 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 the Earth's climate on a decadal scale.

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 high spatial resolution and frequent temporal sampling (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, 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 National Center Atmospheric Research (NCAR) Junior Faculty Forum on biomass burning was convened in July 2010 in Boulder Colorado to bring together 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 to evaluate the state of biomass burning research including nascent and emerging issues, discuss 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, please see the wiki of the Junior Faculty Forum 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. For global studies, satellite fire products have been produced from ATSR, SPOT Vegetation, and MODIS. Fire products from 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 now include Fire Radiative Power, 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 practice. The role of fire in agricultural practice, 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 factor 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 FTIR have made possible 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 MODIS, IASI, TOMS, GOME, AIRS, SCIAMACHY, TES, MOPITT, and other instruments. These data have also been used to quantify the contribution of biomass burning to regional and interannual variation 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 multi-year 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 meter length scales have shed light on the complex dynamics in the immediate vicinity of fires, and the feedbacks of these dynamics on fine-scale meteorology. 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. Simulations of direct radiative impacts of smoke and feedbacks to meteorology, such as the smoke semi-direct effect, are now incorporated as standard modules in some weather forecast models. Smoke emissions data are fed into global models, sometimes on a near real-time basis, to analyze and forecast the 3D distribution of aerosols and visibility.

Model outputs are used for 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, but the radiative extinction of a smoke layer generally reduces the solar input at the surface, cooling the surface. State-of-the-art weather models have started to incorporate direct, indirect, and semi-direct effects of smoke aerosol emissions.

Integration of model and observational data on fire. Inverse methods and data assimilation techniques are becoming useful in estimating biomass burning emissions based on the downwind abundance of chemical constituents in the atmosphere. This has been largely facilitated by the availability of satellite observations (e.g. CO, AOD, NO_2, O_3) and by the advances in modeling the transport and chemistry of fire emissions.

“Top-down” emission estimates are derived from statistically weighted comparisons between simulated and observed biomass burning plume events. These estimates provided opportunities to evaluate and understand the accuracy of the bottom-up emission inventories. To date, validation of these inventories has been carried out either through dedicated field campaigns (e.g. SAFARI) or through indirect comparisons with smoke observations. Results from inverse modeling experiments provided top-down constraints on the magnitude and seasonality of regional emissions. These results have highlighted the persistent discrepancy between bottom-up estimates of emissions and inverse results based on downwind measurements.

NEAR-TERM SCIENTIFIC DIRECTIONS

The discussion at the NCAR Junior Faculty Forum made clear that this is a period of intense research activity in the area of 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 factors of difference between different inventories, and between bottom-up and top-down estimates. There are several reasons for this:

- 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 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.

While 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. The MODIS instruments on Terra and Aqua, with overpass time differing by 3 hours, show important differences in patterns of fires.

Geostationary sensors can observe the entire diurnal cycle; work remains to characterize the geostationary fire detection products and apply them to better understand diurnal variation in fire behavior.

Several different experiments have shown indirectly that the viewing geometry is a key determinant of the fire detection efficiency for active fires. MODIS pixel geometry varies greatly across the swath. The ASTER instrument has provided the best characterization to date of the MODIS active fire products; however, since this sensor has a narrow swath and flies on the same platform as MODIS-Terra, it cannot be used to characterize geometric or diurnal variation in fire detection. Geometric effects have been documented but now need to be quantified; this effort will require the use of multiple high-resolution sensors.

As we refine our understanding of sensors currently in use, we must apply this knowledge to emerging sensors, especially geostationary sensors that will extend geostationary fire detection with frequent repeat 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 could become a key resource for a wide range of studies on the atmospheric and land surface effects of fires.

The potential of directly quantifying the energy release of a fire (the Fire Radiative Power, FRP) using satellite observations has been demonstrated in field campaigns and limited satellite experiments. Many of the factors that determine how much of a fire's energy will reach the sensor require more study. The experiments that demonstrate most clearly the information content of FRP involve averaging of hundreds to thousands of pixel-level observations over broad geographic areas and long time periods. The signal-to-noise ratio of FRP measurements must be quantified, as this determines the scales at which this information can be used to quantify fire behavior. Furthermore, current retrieval of FRP per pixel can be insufficient for various needs, including the estimate of fire temperature and fire size, which are important parameters for studying the fire dynamics, fire weather, and the injection height of the smoke plume. New or improved methods to retrieve sub-pixel fire information are necessary to drive models of broad-scale fire behavior.

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.

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 fine-scale 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 integration of physical treatments of plume development in transport models.

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 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, in order to more effectively isolate the impact of smoke on cloud properties and precipitation.

Beyond quantifying fire behavior, the data scientists rely on for partitioning emissions into various trace gas species and particle types is 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 improved understanding of the factors governing species partitioning in smoke, and eventually lead to better physical models of emissions.

Global and regional-scale transport experiments have shown that current emissions inventories do not reproduce well the magnitudes of downwind pollutants. The two species that have the densest measurements and the strongest signal of burning emissions are carbon monoxide and aerosol particles, and 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 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 have been historically designed to derive emission estimates for large geographical areas. More regionally focused experiments are needed to exploit the fine scale spatio-temporal patterns observed in biomass burning plumes. This type of experiment will provide opportunities to understand the inherent differences on fire emission characteristics across different ecosystems and land use practices. In addition, more sophisticated inverse modeling 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 estimates and teams doing atmospheric simulations must be pursued to achieve this.

The breadth of observations and physical mechanisms that must be integrated to effectively study biomass burning is beyond the scope of individual research groups. This effort is necessarily interdisciplinary, and requires close collaboration between teams emphasizing different areas. Many of the advances in this field in the near and medium term will come from synthesis of research results from diverse sources.

OUTLOOK FOR THE FUTURE STUDY OF BIOMASS BURNING

In a decade, the models used to simulate and forecast biomass burning and its atmospheric effects may look very different from what we use today. Many of the parameterizations and statistical treatments of complex processes stem from limitations in our ability to observe fires and limitations in our mathematical models representing the physical processes that govern fire behavior.

Many of the scientific directions in the previous section pertain to collection of data to refine these statistical treatments. However, as these data are collected and analyzed, the potential for tightly coupled, more mechanistic models must be kept in mind.

It is possible to envision a modeling system where an Earth system model (e.g., coupled weather-fire behavior models coupled with improved online atmospheric chemistry and transport models) replaces many of the statistical and parameterized treatments used currently. 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. 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 from larger meteorological structures, modified for additional heat contributions and composition changes associated with 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 current capabilities. Where observations exist, major computational challenges must still be overcome in the real time modeling of hundreds of chemical species. But most of all, we must improve our understanding of the complexity and variability of fire behavior and fire emissions at landscape scales. 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 just 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 destruction of property by wildfires, to 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 the NCAR Junior Faculty 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.

ACKNOWLEDGEMENT

On behalf of all the participants, we would like to thank the NCAR Advanced Studies Program and the NCAR Early Career Scientist Assembly for hosting this meeting.

FURTHER READING

Crutzen, P. J., and M. O. Andreae, 1990: Biomass Burning in the Tropics: Impact on Atmospheric Chemistry and Biogeochemical Cycles. *Science*, **250,** 1669-1678.

Kaufman, Y. J., and Coauthors, 2003: Fire and smoke observed from the Earth Observing System MODIS instrument - products, validation, and operational use. *Int. J. Remote Sens.*, **24,** 1765-1781.

Reid, J. S., and Coauthors, 2009: Global Monitoring and Forecasting of Biomass-Burning Smoke: Description of and Lessons from the Fire Locating and Modeling of Burning Emissions (FLAMBE) Program. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, **2,** 144-162.

Seiler, W., and P. J. Crutzen, 1980: Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Clim. Change*, **2,** 207-247.

van der Werf, G. R., and Coauthors, 2010: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009). *Atmos. Chem. Phys.*, **10,** 11707-11735.