Forest Ecology and Management 317 (2014) 70–79

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Wildland fire emissions, carbon, and climate: Plume rise, atmospheric transport, and chemistry processes

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ARTICLE INFO

Article history:
Available online 7 March 2013

Keywords:
Wildland fire
Fire emissions
Plume rise
Atmospheric transport
Atmospheric chemistry

ABSTRACT

This paper provides an overview and summary of the current state of knowledge regarding critical atmospheric processes that affect the distribution and concentrations of greenhouse gases and aerosols emitted from wildland fires or produced through subsequent chemical reactions in the atmosphere. These critical atmospheric processes include the dynamics of plume rise, chemical reactions involving smoke plume constituents, the long-range transport of smoke plumes, and the potential transport of gases and aerosols from wildland fires into the stratosphere. In the area of plume-rise dynamics, synthesis information is provided on (1) the relevance of plume height for assessing impacts of gases and aerosol from wildland fires on the climate system, (2) recent scientific advances in understanding the role of multiple updraft cores in plume behavior, and (3) some of the current modeling tools and remote sensing monitoring techniques available for predicting and measuring smoke plume heights. In the area of atmospheric chemistry associated with wildland fire emissions, synthesis information is provided on what is currently known about the atmospheric fate of wildland fire smoke-plume constituents and the relationship of their atmospheric chemistry to radiative forcing. Synthesis information related to long-range atmospheric transport of wildland fire emissions is presented and summarizes many of the recent published observational and modeling studies that provide clear evidence of intercontinental, continental, and regional transport of North American fire emissions, including black carbon, to locations far-removed from the fire-event locations. Recent studies are also highlighted that examined the significance of troposphere-stratosphere exchange processes, which can result in the transport of greenhouse gases and aerosols from North American wildland fires into the stratosphere where they can remain for very long periods of time and alter the radiative balance and typical chemical reactions that occur there. Finally, specific research gaps and needs related to plume dynamics, atmospheric transport and deposition processes, and the atmospheric chemistry of wildland fire emissions are identified and discussed.

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1. Introduction

Greenhouse gases and aerosols emitted from wildland fires are transported away from burning areas due to local atmospheric circulations induced by the fires and ambient atmospheric circulations. The lofting of smoke plumes from wildland fires through plume rise processes to higher levels in the atmosphere is generally followed by the horizontal transport of those plumes to locations far removed from the ignition source of wildland fires. During the vertical rise and the horizontal transport of plumes through the atmosphere, many of the chemical and gaseous species that comprise wildland fire smoke, including greenhouse gases, undergo chemical reactions. These chemical reactions can further affect plume concentrations and distributions of greenhouse gases and aerosols and their ultimate impact on the climate system through radiative forcing. This paper provides an overview and summary of the current state of knowledge regarding critical atmospheric transport and chemistry processes that affect the distribution and concentrations of greenhouse gases and aerosols emitted from wildland fires or produced through subsequent chemical reactions in the atmosphere. Current modeling tools and monitoring techniques used for assessing wildland fire plume behavior are also discussed. Finally, suggestions for future research are provided to further advance our understanding of the critical atmospheric processes involved in wildland fire plume dynamics.

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0378-1127/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.foreco.2013.02.001

2. Plume rise processes

Smoke plume-rise height is characterized as the maximum height a smoke plume can reach vertically in the atmosphere. For a well-developed plume, it is measured at the point where a smoke plume bends from vertical rising to horizontal transport. Typical smoke plume-rise heights range from hundreds of meters for prescribed fires to thousands of meters for wildfires, with occasional stratospheric penetration occurring for the most energetic fires (Gabbert, 2010). Plume rise is an important factor for local and regional air quality. Fire emissions injected at higher elevations are likely to be transported out of the local burn site and may affect air quality in downwind locations, including sensitive populations and urbanized areas. Furthermore, heat, water, and particles (including black carbon and other aerosols) emitted from fires impact atmospheric thermal, dynamical, and hydrological conditions and processes (Liu et al., 2014). Plume rise and the vertical distribution of gases and particles within smoke plumes are critical factors in assessing the downwind impacts of smoke plumes from wildland fires.

2.1. Modeling tools

Plume height is a parameter required by many regional air quality models. The Community Multiscale Air Quality (CMAQ) model and software suite (Byun and Ching, 1999; Byun and Schere, 2006) incorporates the Sparse Matrix Operator Kernel Emissions Modeling System (SMOKE) (Houyoux et al., 2002) to provide plume rise as part of initial and boundary conditions for elevated emission sources. In an early smoke model version of CMAQ and SMOKE, the Briggs scheme (Briggs, 1975) originally developed for power plant stacks was used to calculate fire smoke plume rise. The Briggs scheme is a two-thirds law integral model based on differential equations governing fluxes of mass, momentum, and energy through a plume cross section. Plume rise is calculated from both emission properties, such as initial buoyancy flux and exit velocity, and ambient properties, such as wind and thermal stability. The performance of the Briggs scheme is dependent on the relative importance of these properties. Performance is enhanced if thermal turbulence generated by the plume buoyancy dominates over mechanical turbulence generated by the ambient airflow. The typical plume rise scenarios are power plant stacks and smoke plumes in relatively calm wind conditions. Thus, in theory, if the plume momentum flux dominates, the Briggs scheme may not perform well. Guldberg (1975) compared the accuracy of the Briggs scheme with two other schemes in modeling the heights of hot, buoyant plumes and found that the Briggs scheme best predicted the observed plume heights during periods of low wind speed.

Analysis of the valid applications of the Briggs scheme emphasizes the importance of developing smoke plume rise schemes specifically for wildland fires. A number of wildland fire smoke plume rise models have been recently developed. These models can be divided into three types (Empirical, Dynamic, and Hybrid models). Empirical models are developed based on field and laboratory measurements and analyses using statistical methods or similarity theory. Expert opinion is used in some models. Empirical models are algebraic expressions that require no time or space integration. Because of simplicity, empirical models are easily used by fire and air quality managers. Harrison and Hardy (2002) developed an empirical model to estimate plume rise using peak flame power based on the measurements of a large number of prescribed burns in the northwestern US. The Briggs scheme was modified in the Fire Emission Production Simulator (FEPS) scheme by converting the heat flux from a fire to a buoyancy flux (Anderson et al., 2004). The Western Regional Air Partnership (WRAP, 2005) used a climatological method by specifying predefined plume bottom and plume top and a predefined diurnal temporal profile for each fire.

Dynamical models are the second type of wildland fire smoke plume rise models. They consist of differential equations governing fluxes of mass, momentum and energy with solutions found through time and/or space integration. Because of their complexity, dynamical models are usually employed as research tools. One example is the dynamical model (Freitas et al., 2006) based on a one-dimensional dynamic entrainment plume model (Latham, 1994). An extended set of equations, including the horizontal motion of the plume and the additional increase of the plume size, are solved to explicitly simulate the time evolution of the plume rise and determine the final injection layer. Dynamical models, specifically high resolution atmospheric boundary-layer models and large-eddy-simulation models that are able to resolve atmospheric circulations and thermodynamics within forest vegetation layers, are now being applied to prescribed fire episodes in order to assess the impacts of forest vegetation on initial plume rise and local smoke dispersion. For example, Kiefer et al. (2011a, 2011b) developed a canopy sub-model for the Advanced Regional Prediction System (ARPS) (Xue et al., 2000, 2003), and then used ARPS to simulate the effects of forest vegetation on the atmospheric boundary-layer dynamics that influenced the initial plume rise from a prescribed fire in the New Jersey Pine Barrens. Results from their work suggest that forest vegetation has a significant impact on atmospheric turbulence and the resulting vertical and horizontal dispersion of wildland fire smoke emissions in the lower atmospheric boundary layer.

The third type is a hybrid of the empirical and dynamic smoke models. One example is Daysmoke (Achtemeier et al., 2011), which simulates smoke particle movements using statistical and stochastic relations. Daysmoke consists of four sub-models: an entraining turret model, a detraining particle model, a large eddy parameterization for the mixed boundary layer, and a relative emissions model that describes the emission history of the prescribed burn. These relations appear in differential equations and therefore require time and space integration. A rising smoke plume is described by a train of rising turrets of heated air that sweep out a three-dimensional volume defined by plume boundaries expanding with time through entrainment of surrounding air through the sides and bottoms as they ascend. Daysmoke was developed specifically for prescribed burning and is an extension of ASHFALL, a model developed to simulate deposition of ash from sugar cane fires (Achtemeier, 1998). In comparison with wildfires, the role of buoyancy generated by prescribed fires often is relatively smaller because of the smaller amount of heat released. Mechanical turbulence in the boundary layer is usually more important than the buoyancy associated with prescribed fires in governing how prescribed fire smoke plumes behave in the boundary layer.

Smoke transport and dispersion models are being used operationally on prescribed burns and wildfires to simulate and predict the transport and dispersion of smoke and to estimate particulate matter concentration at ground level. These modeling tools fall into several categories that are described and summarized in Goodrick et al. (2012): box models, Gaussian plume models, Lagrangian puff and particle models, Eulerian grid models, full physics models, and smoke modeling frameworks. The complexity of these models range from a simple box representing an airshed with a defined top of the mixing layer and horizontal dimensions defined by the spatial extent of the wildland fire airshed, to more complex modeling frameworks that link individual fuel loading, fuel consumption, emissions, and smoke trajectory and concentration models in a modular framework to predict real-time smoke trajectories and concentrations.