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Wildland fire emissions, carbon, and climate: Wildfire–climate interactions

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ABSTRACT

Increasing wildfire activity in recent decades, partially related to extended droughts, along with concern over potential impacts of future climate change on fire activity has resulted in increased attention on fire–climate interactions. Findings from studies published in recent years have remarkably increased our understanding of fire–climate interactions and improved our capacity to delineate probable future climate change and impacts. Fires are projected to increase in many regions of the globe under a changing climate due to the greenhouse effect. Burned areas in the western US could increase by more than 50% by the middle of this century. Increased fire activity is not simply an outcome of the changing climate, but also a participant in the change. Smoke particles reduce overall solar radiation absorbed by the Earth's atmosphere during individual fire events and fire seasons, leading to regional climate effects including reduction in surface temperature, suppression of cloud and precipitation, and enhancement of climate anomalies such as droughts. Black carbon (BC) in smoke particles displays some different radiation and climate effects by warming the middle and lower atmosphere, leading to a more stable atmosphere. BC also plays a key role in the smoke-snow feedback mechanism. Fire emissions of CO_2, on the other hand, are an important atmospheric CO_2 source and contribute substantially to the global greenhouse effect. Future studies should generate a global picture of all aspects of radiative forcing by smoke particles. Better knowledge is needed in space and time variability of smoke particles, evolution of smoke optical properties, estimation of smoke plume height and vertical profiles and their impacts on locations of warming layers, stability structure, clouds and smoke transport, quantification of BC emission factors and optical properties from different forest fuels, and BC's individual and combined roles with organic carbon. Finally, understanding the short- and long-term greenhouse effect of fire CO_2 emissions, increased capacity to project future fire trends (especially mega-fires), with consideration of climate–fuel–human interactions, and improved fire weather and climate prediction skills (including exploring the SST-fire relations) remain central knowledge needs.

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1. Introduction

Wildfires and climate are two closely related Earth system processes. It has long been recognized that atmospheric conditions are an environmental factor for wildfires. Depending on their time scales, atmospheric conditions are classified into weather and climate. Weather is commonly defined as the day-to-day state (temperature, humidity, wind, etc.) and processes (cloud and precipitation, fronts, jets, troughs, ridges, etc.) of the atmosphere in a region and their short-term (up to weeks) variations, whereas climate is defined as statistical weather information over a certain period (usually 30 years) (www.diffen.com/difference/Climate_vs_Weather). Climate also generally serves as a reference to atmospheric variability on time-scales that exceed the limit of deterministic predictability, about 2–3 weeks (Wallace and Hobbs, 2006).

Atmospheric conditions for fires are accordingly classified into fire weather and fire climate (Pyne et al., 1996). Fire weather is one of the factors determining occurrence and behavior of individual fires within a fire season (Flannigan and Wotton, 2001). Fire climate, meanwhile, is a synthesis of daily fire weather that describes statistical features (average, variation, etc.) of fire weather. Fire climate determines the atmospheric conditions for fire activity at time scales beyond a fire season (Flannigan and Wotton, 2001).

Wildfires can impact atmospheric conditions at various spatial and temporal scales through emissions of gases, particles, water, and heat. Fire emission components (Table 1) with significant atmospheric effects include CO_2 (about 71% of mass), and organic and element or black carbon accounting for about 0.24% and 0.02%, respectively. Organic carbon and black carbon are carbonaceous aerosols that scatter and absorb atmospheric radiation, respectively. The percentage of a component varies considerably

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Table 1
Emissions from wildfires. The mass amount is grams of emission/kilogram of fuel burned. The letter "d" represents particle diameter (from NRC, 2004).

Emissions	Mass	%
Carbon Dioxide	1564.8	71.44
Carbon Monoxide	120.9	5.52
Organic Carbon	5.2	0.24
Elemental Carbon	0.4	0.02
Particulate matter $d < 2.5\mu$	10.3	0.47
Particulate matter $2.5\mu < d < 10\mu$	1.9	0.09
Particulate Matter $d > 10\mu$	3.8	0.17
Nitric Oxide	8.5	0.39
Methane	5.9	0.27
Non-methane Hydrocarbon	4.3	0.20
Volatile Organic Compounds	5.2	0.24
Water	459.2	20.97

from one burn case to another. For example, CO_2 reported by Urbanski et al. (2008) accounts for 87–92% of total carbon burned. Smoke particles can directly affect atmospheric radiative transfer through scattering and absorbing radiation (mainly short-wave radiation) and indirectly through changing cloud properties with smoke particles acting as cloud condensation nuclei (CCN) (Fig. 1). Changes in radiative forcing lead to subsequent changes in air temperature, humidity, and wind. The changes can happen at short time scales of minutes and days. Additionally, CO_2 is a dominant component of fire emissions. As a greenhouse gas (GHG), CO_2 absorbs atmospheric long-wave radiation emitted from the surface-atmosphere system and therefore is a primary factor in global warming. This usually happens over a long-term period of decades. Heat energy released from fires can also modify the local atmospheric thermodynamic structure, turbulence regime, and wind patterns, as well as other atmospheric thermal and dynamical properties and processes. Water vapor released from fire can increase atmospheric humidity, favoring formation of clouds and fog. Similar to smoke particles, the released heat and water can affect atmospheric conditions at short-time scales. Fires also remove certain amount of vegetation coverage or reduce vegetation density, which will affect heat, water, and trace gas exchanges with the atmosphere at both short- and long-term scales, which will in turn affect weather and climate.

Gas and particle emissions from fires alter atmospheric properties (air temperature, humidity, clouds, wind and turbulence) which in turn will modify fuel conditions, especially fuel moisture, at different time and space scales by. For example, heat release has an immediate impact on winds which changes the surface fluxes of heat and moisture and thereby alters fuel moisture and fuel temperature, which are important factors for fire occurrence (ignition and risk) and fire spread. Solar heating of fuel particles is a prime driver of fuel temperature and fuel moisture (see e.g. Rothermek et al., 1986; Cohen and Deeming, 1985; Carlson et al., 2007). Changes in atmospheric moisture content and cloud properties due to fire emissions can alter the amount of solar radiation reaching the surface. Fuel particles absorb solar radiation resulting in a temperature increase of the fuels. Also, exposed ground surfaces are also heated by solar radiation and subsequently transfer heat to adjacent fuel particles. However, CO_2 emissions contribute to global CO_2 levels and impact climate over a decadal or longer time-scale. Future changes in climate may impact future fire behavior. Smoke particles can have immediate (shading of fuels from solar radiation, impact on local atmospheric structure) and longer-term impacts that act over larger spatial scales on fire behavior (aerosol impacts on radiation and cloud processes may act over time periods of hours to days via impact larger areas or be realized some distance from the fire source).

While research has historically focused on the fire–weather interactions, increasing attention has been paid in the past few decades to fire–climate interactions. A contributing factor to this emerging emphasis is the evidence that wildfires, especially large wildfires, have increased in recent decades (Piñol et al., 1998; Goldammer, 2001; Gillett et al., 2004; Reinhard et al., 2005; Westerling et al., 2006), partially related to extreme weather events such as extended droughts (Goldammer and Price, 1998; Stocks et al., 2002). Persistent weather anomalies can directly impact fire activities during a fire season. Under prolonged warm and dry conditions, fires are easier to ignite and spread and a fire season often becomes longer. The duration of the fire season may also be impacted by earlier beginning due to low snow pack or early spring snow melt (Westerling et al., 2006). Another factor is concern regarding the potential impacts of future climate change on fire activity. Many climate models have projected significant climate change during this century due to the greenhouse effect (IPCC, 2007), including an overall increase in temperature worldwide and a drying trend in many subtropical and mid-latitude regions. It appears likely that wildfires will increase in these regions.

Knowledge of fire–climate interactions is essential to understanding fire and climate variability and change. First, seasonal

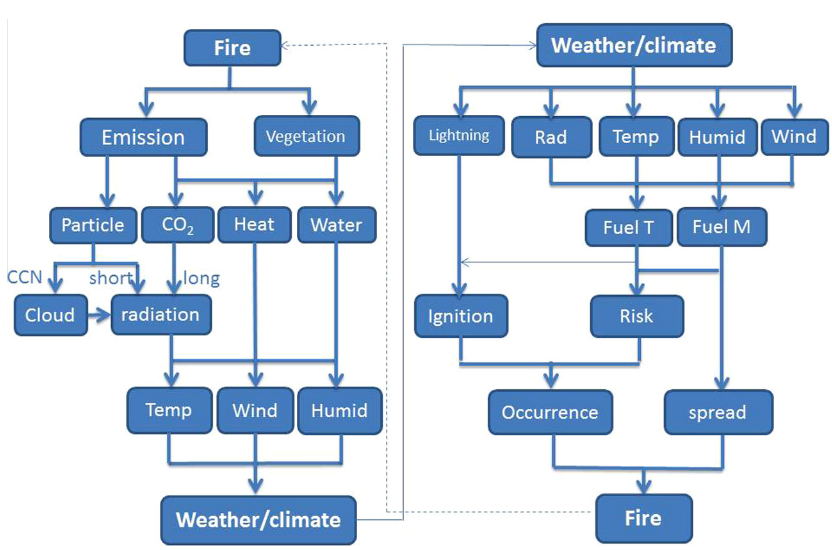

Fig. 1. Diagram of physical processes for fire's impacts on weather and climate and feedbacks.