

# Chapter 4

## Smoke Plume Dynamics



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**Abstract** Smoke plume dynamic science focuses on understanding the various smoke processes that control the movement and mixing of smoke. A current challenge facing this research is providing timely and accurate smoke information for

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the increasing area burned by wildfires in the western USA. This chapter synthesizes smoke plume research from the past decade to evaluate the current state of science and identify future research needs. Major advances have been achieved in measurements and modeling of smoke plume rise, dispersion, transport, and superfog; interactions with fire, atmosphere, and canopy; and applications to smoke management. The biggest remaining gaps are the lack of high-resolution coupled fire, smoke, and atmospheric modeling systems, and simultaneous measurements of these components. The science of smoke plume dynamics is likely to improve through development and implementation of: improved observational capabilities and computational power; new approaches and tools for data integration; varied levels of observations, partnerships, and projects focused on field campaigns and operational management; and new efforts to implement fire and stewardship strategies and transition research on smoke dynamics into operational tools. Recent research on a number of key smoke plume dynamics has improved our understanding of coupled smoke modeling systems, modeling tools that use field campaign data, real-time smoke modeling and prediction, and smoke from duff burning. This new research will lead to better predictions of smoke production and transport, including the influence of a warmer climate on smoke.

**Keywords** Measurement · Modeling · Management · Plume rise · Smoke impacts · Smoke plume · Transport and dispersion

## 4.1 Introduction

### 4.1.1 *Scientific Significance*

The fate of smoke from a wildland fire depends in large part on the airflow carrying it away from the fire which can involve a complex interaction of eddies that may occur near the ground or expand beyond the atmospheric mixed layer. The buoyancy of smoke and ambient atmospheric conditions determines how high and how quickly the smoke rises, and thus where it travels. Understanding the processes that control the movement and mixing of smoke is essential to any endeavor to predict (and

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manage) the impacts of smoke on public health and safety, including air quality, visibility, aviation, and climate. These processes are commonly referred to as “plume dynamics”.

An improved scientific understanding of smoke plume dynamics will allow for more accurate assessments and predictions of the fate and impacts of wildland fire emissions. These emissions are a major source of particulates, black carbon, and organic carbon, and can contribute substantially to the formation of aerosols and gases that comprise air pollution and haze (Baars et al. 2011; Strand et al. 2011; Wiedinmyer et al. 2011; Larkin et al. 2014). The transport and deposition of black carbon to the Arctic (Larkin et al. 2012; Hao et al. 2016) can reduce surface albedo which enhances snow and ice melt (Evangelidou et al. 2016). Some wildland fire smoke plumes can penetrate the tropopause and mix into the stratosphere to affect ozone, carbon monoxide, carbon dioxide, reactive nitrogen, and water vapor concentrations at high altitudes (Jost et al. 2004; Chap. 6).

Accurate characterization of smoke plume dynamics can improve our understanding of smoke impacts on atmospheric radiation, weather, climate, and photochemical processes. Smoke particles modify atmospheric radiative transfer directly through light scattering and absorption of solar radiation, and indirectly by influencing cloud formation (Bauer and Menon 2012). This potentially changes atmospheric temperature, stability, and convection. Depending on the photochemical environment, ozone enhancement from biomass burning has been observed in many instances (Brey and Fischer 2016). Smoke plume temperature usually decreases with height, which affects photochemical reaction rates for ozone production (Lim et al. 2019). This further affects secondary organic carbon (SOC) production.

Smoke plume dynamics provide the scientific foundation for developing predictive models and tools appropriate for wildland fire applications. For example, plume rise is an important property determining the local and regional impacts of smoke. Emissions that remain within the mixing layer can be influenced by topography (Chap. 5) and the diurnal change in the mixing layer, affecting local areas near the fire site. In addition, a smoke plume can penetrate into the free atmosphere and high lofted smoke particles can be transported tens of kilometers, affecting regional air quality downwind. For example, locations in Idaho often receive smoke transported from California wildfires and ozone concentrations in eastern US cities can be affected by long-range transport of smoke from Canada and the western USA (Wilkins et al. 2020). Many smoke and air quality models require estimates of plume rise, whereby particulates and gases emitted from wildland fires are distributed into model-domain atmospheric layers above fires. Improvements in smoke modeling can be made by basing these estimates on a sound scientific understanding of how fire-induced convective plumes interact with the atmosphere, from the flaming regions immediately above the fire to much higher in the atmosphere.

## **4.1.2 Management Significance**

The area burned by wildfire, fire severity, and the size of the largest fires have increased in the USA over the past 20 years (Dennison et al. 2014). Smoke from wildland fires has been associated with increased physician and emergency room visits, hospital admissions, and mortality (Chap. 7). Illnesses attributed to smoke exposure can also result in absences from work and school, affecting economic productivity and educational achievement, respectively. Fires and smoke also are increasingly affecting urban areas, leading to air pollution and visibility problems (Mass and Ovens 2018). Dispersal of smoke across roadways and airports can be a major concern as very high concentrations of fine particulates can significantly reduce motorist visibility during both day and night.

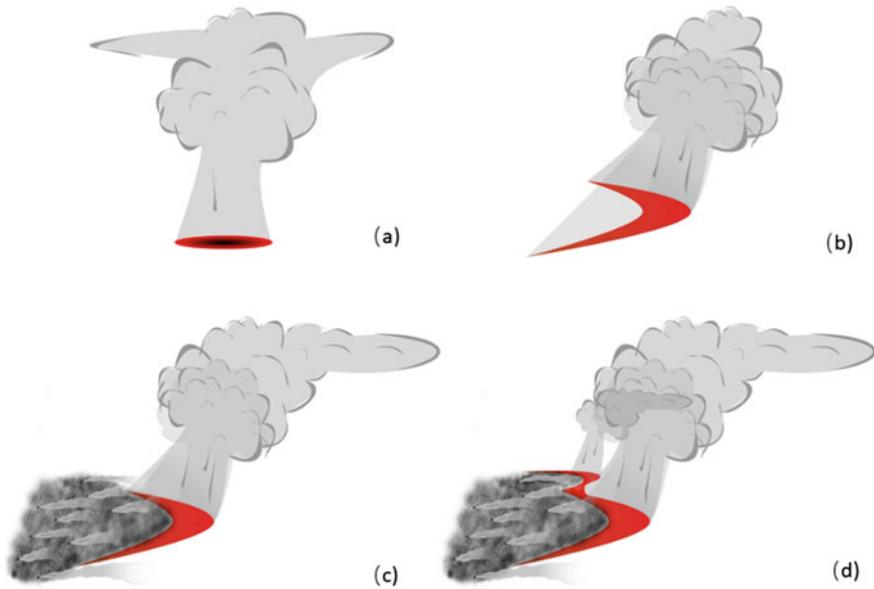
Modeling wildland fire smoke plume dynamics helps provide important information for decision makers and society (Chap. 8). An understanding of plume dynamics contributes to an accurate air quality forecast and helps air quality and land managers answer the most commonly asked public questions during smoke events: (1) Where is the smoke coming from?, (2) How long will it last?, (3) What are the pollutant concentrations?, and (4) Should I be concerned? Knowledge of the spatial and temporal smoke patterns helps air quality forecasters warn a potentially affected community of the likely location, magnitude, extent, and duration of smoke-related air quality impacts, enabling people to modify their behavior to reduce exposure to pollutants. This chapter therefore synthesizes existing research and knowledge on smoke plume dynamics. The objectives are to assess the current state of science, mainly based on studies conducted in the past decade, identify research gaps, provide a vision for improving smoke dynamics science, and describe emerging issues and challenges.

## **4.2 Current State of Science**

### **4.2.1 Theoretical Framework**

#### **4.2.1.1 Conceptual Models**

The simplest conceptual model of a plume begins with a point, or at least an axially symmetric, uniform source (Fig. 4.1a). This is similar to the smokestack and mathematical plume models developed for smokestack plumes (Briggs 1982), which are still the most common models used for plumes from wildfires. The plume simulated using these models depends on buoyancy flux, stability, vertical profile of wind, and distance in the downwind direction from a fire, expanding as it mixes with the environment.



**Fig. 4.1** Conceptual smoke plume models. **a** Axisymmetric, simple updraft plume model. **b** Simple wildland fire plume model; a fire with a flaming front and weaker flanks produces a single plume as wind moves the fire forward. **c** Wildfire plume model including residual smoldering behind the flaming front. **d** “Complete” wildfire plume model; multiple flaming head regions produce multiple updraft cores; smoldering combustion behind the front produces smoke, part of which is entrained into the updraft cores, part of which remains separate and near the ground

However, wildland fire practitioners and scientists have long recognized the need for a conceptual and mathematical model that better reflects the geometry and environment typical of a wildland fire in a complex atmosphere. The most basic wildfire-specific conceptual model with one primary updraft is shown in Fig. 4.1b, with a curved flaming front that is more vigorous at the downwind head than on the flanks. At present, there are no mathematical models comparable to Briggs (1982) that incorporate the specific features—variable heating and noncircular shape—that differentiate Fig. 4.1b from Fig. 4.1a.

This fire-specific model is still too simplistic, and the scientific and operational questions regarding plume dynamics require a more complex and physically complete model. Specifically, in a real fire, flaming and smoldering combustion often occur simultaneously and near one another. The area behind the flaming front often continues to smolder after the front passes (Fig. 4.1c), producing smoke that may be entrained into the rising plume, or remain near ground level and disperse more or less independently.

In most wildfires, and in some large prescribed fires, the geometry of the flaming front may result in multiple flaming fronts, each producing a distinct plume updraft, or core (Fig. 4.1d). Different cores may rise to different heights and distribute smoke

into different, possibly overlapping, layers of the atmosphere. This requires a more complex model, accounting for varying scales of eddies and turbulence, effects of vegetation and fuel structure on fire and smoke, sloping terrain, and varying atmospheric stability.

In addition to being transported, the constituent gases and particulates in a fire plume undergo a number of chemical reactions, but these are not generally considered part of plume dynamics. Rather, they are commonly described as plume chemistry. One exception to this is the role of moisture, which is usually present in sufficient quantity, and with sufficient latent heat, to affect smoke rise and generate clouds. Although it constitutes a small part of the total mass, the presence of this moisture can modify the distribution of smoke and influence smoke chemistry (Chap. 6). Plume moisture depends on environmental conditions—both atmospheric and vegetative—which vary as a function of location, season, and time of day. A representative range can be  $1 \text{ g kg}^{-1}$  to  $15 \text{ g kg}^{-1}$  of dry air. This chapter does not consider chemistry other than moist thermodynamics, which relies on the presence of moisture in the plume (see Chap. 6).

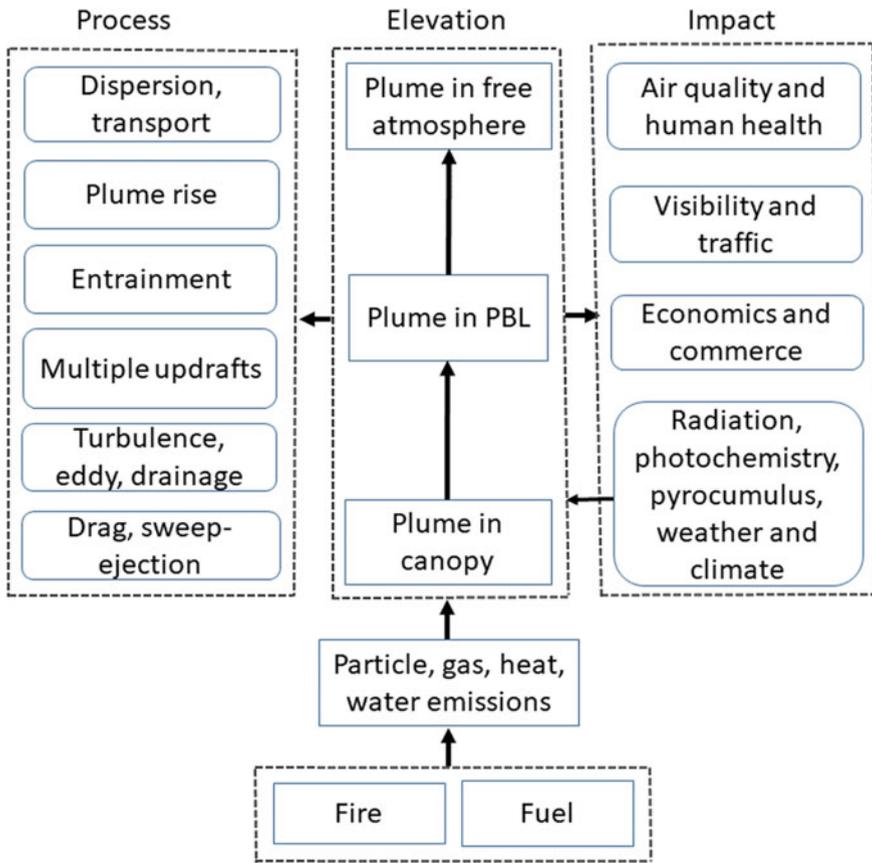
#### 4.2.1.2 Physical Processes

The major physical processes of smoke plume dynamics are shown in Fig. 4.2. Major properties include fire size, fire emissions, ambient atmospheric stratification, turbulent mixing, wind shear, and latent heat released from the condensation of water (Paugam et al. 2016). After being emitted, smoke particles and gases move through the vegetation canopy, the planetary boundary layer, and sometimes into the free atmosphere. The concentrations and three-dimensional dynamical spatial structure and temporal evolution of smoke plumes are determined by the processes of: eddies, turbulence, smoke–canopy interactions, plume rise, dispersion, transport, multiple updrafts, pyro-convection, entrainment of the ambient air, and smoke-induced radiative and cloud disturbances.

### 4.2.2 *Smoke Measurements*

#### 4.2.2.1 Smoke Structure and Atmospheric Disturbances

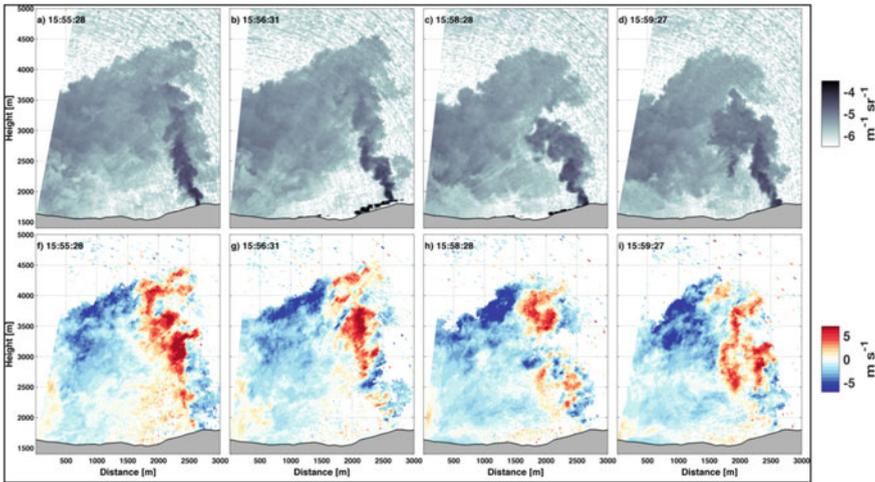
Limited observations of the fire environment during various experimental fires, prescribed fires, and wildfires (Heilman et al. 2014; Clements and Seto 2015; Clements et al. 2019) have focused mostly on fire spread, fire behavior, and other aspects of the fire environment. Recent field studies have focused on fire–atmosphere interactions in grasslands (Clements and Seto 2015; Clements et al. 2019), and forested environments (Heilman et al. 2014; Seto et al. 2014; Clements and Seto 2015), with a small emphasis on ignition and combustion and a large emphasis on



**Fig. 4.2** Schematic illustration of smoke processes and relations, including components presented in other chapters of this book

near-surface atmospheric feedbacks. Clements et al. (2019) have summarized recent field campaigns to study fire spread and fire–atmosphere interactions.

The Rapid Deployments to Wildfires Experiment (RaDFIRE) (Clements et al. 2018) sampled 22 wildfire plumes using a mobile atmospheric profiling system (Clements and Oliphant 2014) equipped with a scanning Doppler Lidar. This campaign included observations of plume and wildfire phenomena including rotating convective plumes, plume interactions with stable layers, multilayered smoke detrainment, plume entrainment processes, pyro-cumulus and pyrocumulonimbus, and smoke-induced density currents formed by smoke-shading (Lareau and Clements 2015, 2016, 2017). The mobile Doppler Lidar systems were especially valuable because of their high resolution and ease of mobility. Figure 4.3 shows a series of Lidar images with detailed, coherent plume structures from the Lidar observations (Lareau and Clements 2017) taken during the El Portal fire near Yosemite National



**Fig. 4.3** Doppler Lidar range-height indicator scans showing plume rise, smoke backscatter (a–d), and radial velocity (f–i). Reddish shading indicates flow away from the Lidar, bluish shading indicates flow toward the Lidar; time is Pacific Daylight Time. Ambient wind is from right to left in the panels. From Lareau and Clements (2017) © American Meteorological Society, used with permission

Park (California) on July 28, 2014. Strong updraft cores and subsequent detrainment downwind of the upper plume are evident in the radial velocities (Fig. 4.3f–i). Near-surface indrafts of  $\sim 2\text{--}3\text{ ms}^{-1}$  extend approximately 1 km away from the column base.

Disadvantages of Doppler Lidars are (1) attenuation in optically thick plumes (Lareau and Clements 2016), (2) fairly slow scan speed ( $1\text{--}2^\circ\text{s}^{-1}$ ) to resolve plume structures when compared to radars ( $>10^\circ\text{s}^{-1}$ ), and (3) lack of polarization in the Lidar beam. Dual-polarized (or Dual pol) Doppler radars transmit and receive both horizontally and vertically orientated beams, providing measurements of the size and shape of particles (pyrometeors [large debris lofted above wildfires that are composed of the by-products of combustion of the fuels], ash, and debris) within the plume. McCarthy et al. (2018) demonstrated the use of mobile X-band dual-polarized Doppler radar for studying wildfire plumes. They sampled bushfire plumes in Australia, with correlation coefficients  $<0.5$  between radar beams within smoke plume in horizontal and vertical directions, which is similar to what other studies have measured (Melnikov et al. 2009; Lang et al. 2014; Lareau and Clements 2016). This range makes it easy to distinguish between the smoke plume and hydrometeors, because correlation coefficients of rain are mostly greater than 0.6.

Extreme wildfire updrafts were measured during the 2016 Pioneer Fire in Idaho using an instrumented aircraft and airborne Doppler cloud radar (Rodriguez et al. 2020). Updraft velocities of  $58\text{ m s}^{-1}$  were observed deep within the plume at altitudes of 2 km and 3 km above ground level. This updraft core was flanked on its edges with downdrafts of  $30\text{ m s}^{-1}$ . The observed updrafts were below the cloud base and a

developing pyrocumulonimbus, indicating that the primary mechanism for the strong updrafts was sensible heat flux associated with the fire front.

#### 4.2.2.2 Plume Rise

A number of techniques have been used to determine the height of smoke plumes, including Lidar/radar detection, imaging, airborne observations, and plume sampling (Urbanski et al. 2010; Heilman et al. 2014). The smoke plume heights for 20 prescribed fires were measured using a ground-based ceilometer in the southeastern USA (Liu et al. 2012); the results indicated that the average smoke plume height was approximately 1 km, with plume heights trending upward from winter to summer. Lidar instruments aboard satellites have been used to detect smoke plume height (e.g., Kahn et al. 2008; Raffuse et al. 2012), including the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite (Winker et al. 2007), and the Multi-angle Imaging SpectroRadiometer (MISR) aboard the National Aeronautics and Space Administration (NASA) TERRA satellite (Kahn et al. 2008). These satellite detections found different plume heights (from tropical to boreal fires) and different percentage of plumes that penetrate into the free atmosphere, where smoke particles can be transported long distances downwind. The mean heights of plumes from wildfires in the western and central USA were approximately 2 km and 3 km, respectively (Raffuse et al. 2012).

Several long-term plume-rise datasets have been compiled based on satellite detections for evaluating plume-rise modeling and fire–climate interactions. A five-year plume height climatology derived from MISR observations (Val Martin et al. 2010) was used to evaluate the performance of the dynamical smoke plume-rise model (Freitas et al. 2007). The model simulations generally underestimated the plume-height dynamic range observed by MISR and did not reliably identify plumes injected into the free troposphere. CALIPSO data combined with a trajectory model and the National Oceanic and Atmospheric Administration (NOAA) hazard mapping system generated daily plume-injection height (Soja et al. 2012). Hourly injection profiles of plumes were developed from all fires recorded globally for more than a decade, using a methodology that considers wildfire plumes similar to Convective Available Potential Energy computations (Sofiev et al. 2012, 2013). An observation-based global hourly fire plume-rise dataset for 2002–2012 used a modified 1D plume-rise model based on observed fire size and fire radiative power data as a function of plant functional type for different regions of the world (Wang et al. 2020). The dataset is especially valuable for fire–climate interaction modeling.

#### 4.2.2.3 Plumes from Prescribed Fires

Prescribed fires are used for ecological restoration, fuel treatment, and habitat management in a variety of ecosystems (Chaps. 2, 8). Because prescribed fires and

wildfires typically have different intensities, plume dynamics and environmental impacts of the emissions differ between the two fire types (Williamson et al. 2016). Although it is expected that health impacts from prescribed fire emissions will be less, smoke from prescribed burning can linger for relatively long periods of time, degrade local air quality, and pose a human health risk, due in part to the nature of plume dynamics.

Prescribed fires provide opportunities for safely measuring fire–fuel–atmosphere interactions within and near the fire environment that can help improve our understanding of how fuels, topography, forest canopies, and ambient and fire-induced atmospheric conditions affect fire and local smoke plume behavior. Recent prescribed fire experiments that assessed plume dynamics include:

- The Prescribed Fire Combustion and Atmospheric Dynamics Research Experiment (RxCADRE) conducted in Florida (Clements et al. 2016; Ottmar et al. 2016; Peterson and Hardy 2016).
- Sub-canopy fire experiments in New Jersey and North Carolina (Heilman et al. 2013, 2015; Strand et al. 2013; Seto et al. 2014).
- The FireFlux grassfire experiments conducted over flat terrain in Texas (Clements 2010; Clements et al. 2019).
- Grassfire experiments in complex California terrain (Seto and Clements 2011; Charland and Clements 2013; Clements and Seto 2015).
- Numerous low-intensity fire experiments focused on plume heights, superfog formation, and validation of smoke dispersion models in Florida, Georgia, and Alabama (Achte-meier 2005, 2009; Liu et al. 2009; Achtemeier et al. 2011).

These studies found that even low-intensity prescribed fires can modify ambient atmospheric flow near the fires due to buoyancy at the fire front. Atmospheric turbulence can be maximized just above the canopy and is typically anisotropic, with horizontal turbulent mixing of smoke plumes exceeding vertical mixing. Maximum plume updraft speeds during low-intensity sub-canopy fires typically occur near the canopy top, although downdrafts can also occur in a sub-canopy fire environment. Entrainment of cooler ambient air often occurs on the back side of advancing fire fronts and their associated plumes.

Fire-induced surface-pressure perturbations at fire fronts can increase wind velocity at the base of plumes (Clements and Seto 2015; Clements et al. 2019). Smoke transport and dispersion during low-intensity fires in complex terrain at night are governed by large-scale atmospheric synoptic forcing and buoyancy-related drainage flows. The mixing of warm and moist smoke plumes generated by low-intensity fires with cool and moist ambient nighttime air can generate superfog plumes (a combination of smoke and water vapor that produces zero visibility over roadways; see below and Chap. 3) that are carried downwind of the fire.

#### 4.2.2.4 Field Campaigns

In recent years, several comprehensive field campaigns that combined Lidar, radar, weather towers, aircraft, drones, and satellites to measure smoke plumes over burn sites and downwind from wildfires and prescribed burns have been implemented. These projects include (1) the Fire and Smoke Model Evaluation Experiment (FASMEE) (Prichard et al. 2019), (2) Fire Influence on Regional to Global Environments and Air Quality (FIREX-AQ), and (3) Western Wildfire Experiment for Cloud Chemistry, Aerosol Absorption and Nitrogen (WE-CAN). These projects have investigated physical, chemical, and optical properties of smoke plumes and the associated influences of fuels, fire behavior, fire energy, and meteorology on dynamics of near-source plumes and long-range smoke transport.

### 4.2.3 Smoke Plume Modeling

#### 4.2.3.1 Plume Rise

It is important to obtain dynamic properties at the fire–atmosphere interface (e.g., heat fluxes, exit temperature, velocity) and evaluate their effects on plume rise in order to understand and develop schemes to predict the effects of complex plume structures (e.g., multiple updrafts) on plume rise. Both empirical and physics-based models are available for calculating plume rise (Liu et al., 2010; Paugam et al. 2016).

Empirical models are based on field and laboratory measurements using statistical methods or similarity theory, with algebraic expressions that require no time or space integration. The Briggs scheme originally developed for stack plumes (Briggs 1982) was adapted for fire plumes by including fire heat release (Pouliot et al. 2005) but has been shown to have systemic biases compared with satellite data (Raffuse et al. 2009). It has been used in the Community Multiscale Air Quality (CMAQ) (Byun and Schere 2006) regional air quality model (Baker et al. 2018). A fire plume-rise height parameterization was developed using observation-based plume-rise data for a 10-year period for 15 global wildfire regions (Wang et al. 2020), including nearly 30 parameters, mostly from climate models. Regression models have been used to calculate plume rise of prescribed fires based on measured plume-rise data in the southeastern USA (Liu 2014).

Physics-based models consist of differential equations governing fluxes of mass, momentum, and energy, with solutions found through time and/or space integration. Among the first dynamical models are (1) a one-dimensional model based on the dynamic entrainment plume model that simulates the time evolution of plume rise and determines the final injection layer (Freitas et al. 2007), (2) a parameterization based on an eddy diffusivity/mass flux scheme for modeling shallow convection and dry convection (Rio et al. 2010), and (3) a vertical static model using a concept similar to Convective Available Potential Energy computations (Sofiev et al. 2012, 2013). An atmospheric modeling framework with different plume-rise parameterizations

for a well-constrained prescribed burn found that model results were significantly improved when fire emissions were distributed below the plume top following a Gaussian distribution (Mallia et al. 2018). Daysmoke, a hybrid of the empirical and dynamic smoke models, simulates smoke particle movements using statistical and stochastic relations.

#### 4.2.3.2 Dispersion and Transport

Modeling tools of varying complexity are available for simulating and predicting transport and dispersion of smoke from wildland fires (Goodrick et al. 2013), including:

- Box models such as the Ventilation Index and the Atmospheric Dispersion Index.
- Gaussian plume models such as VSMOKE and the Simple Approach Smoke Estimation Model (SASEM).
- Lagrangian puff or particle models such as CALPUFF (Scire et al. 2000), the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Stein et al. 2015), FLEXPART (Brioude et al. 2013), Daysmoke (Achtmeier et al. 2011), and Planned Burn-Piedmont (PB-P) (Achtmeier 2005).
- Eulerian grid models such as CMAQ, AERO-RAMS (Wang et al. 2006), and the chemistry version of the Weather Research and Forecasting model (WRF-Chem) (Grell et al. 2005).

Many of the Lagrangian puff/particle and Eulerian grid models rely on observed or model-predicted atmospheric variables (e.g., wind fields, temperatures, moisture, turbulence) at different spatial and temporal resolutions to generate predictions of smoke transport and dispersion. For example, CMAQ, the Advanced Regional Prediction System (ARPS) (Xue et al. 2000, 2001), and its canopy sub-model variant (ARPS-Canopy) (Kiefer et al. 2013) have been coupled to the FLEXPART particle dispersion model to allow for mesoscale, boundary-layer, and canopy-scale simulations/predictions of smoke transport and dispersion (Charney et al. 2019).

The WRF model and its atmospheric chemistry (WRF-Chem), large-eddy-simulation (WRF-LES) (Mirocha et al. 2010) and fire (WRF-Fire) variants (see also Chap. 3) have been used to investigate:

- Plume transport and dispersion-related issues, such as the effects of plume dynamics on fire weather (Grell et al. 2011).
- Vertical and horizontal plume transport during boreal wildfires (Thomas et al. 2017).
- The impact of smoke plumes transported from California, Oregon, and Washington on elevated ozone and PM<sub>2.5</sub> in other locations in the western USA (Miller et al. 2019).
- The effects of vortices on plume dispersion and plume rise (Cunningham and Goodrick 2012).

The WRF model has also been coupled with CMAQ to provide smoke transport and dispersion assessments of fire events (e.g., Zou et al. 2019a). Before being superseded by the WRF model in 2010, the 5th Generation Penn State/National Center for Atmospheric Research Mesoscale Model (MM5) was used extensively with CMAQ (e.g., Liu et al. 2009), CALPUFF (e.g., Jain et al. 2007; Larkin et al. 2009), and Daysmoke (e.g., Liu et al. 2010) to conduct smoke transport and dispersion assessments in the USA (Fig. 4.4).

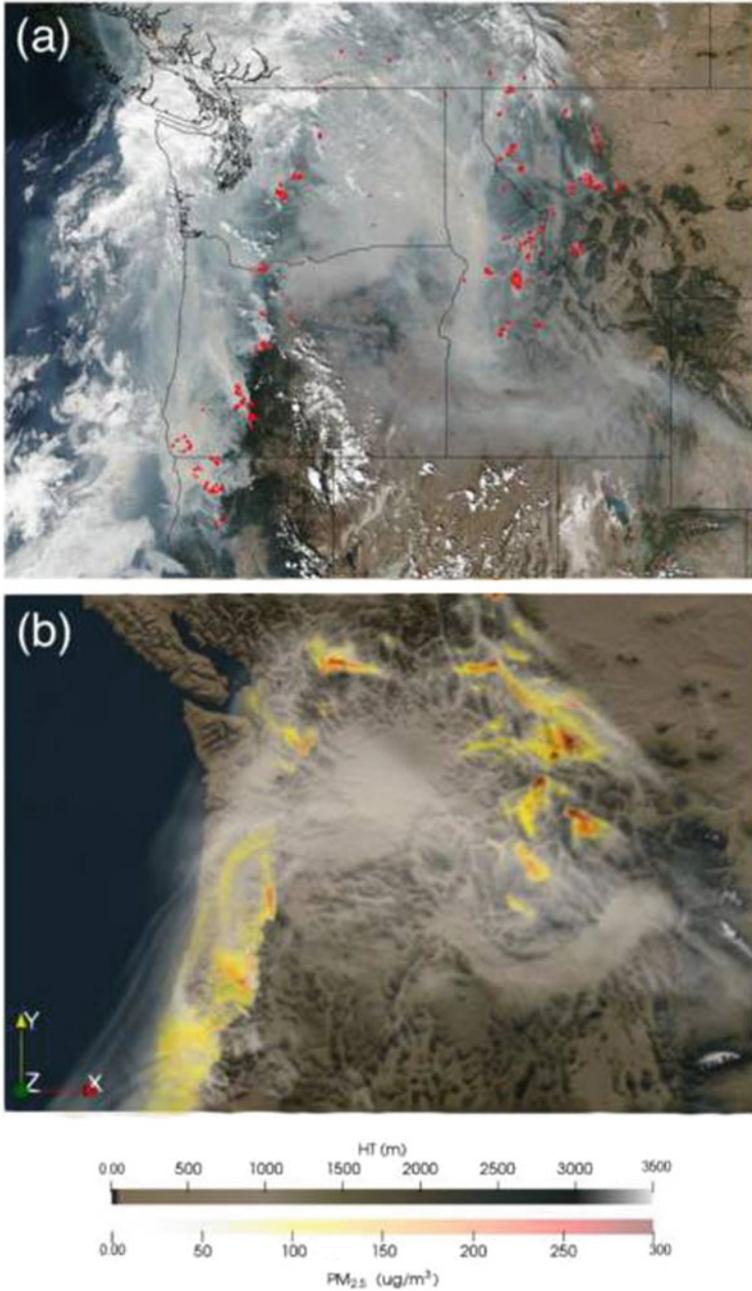
### 4.2.3.3 Nighttime Smoke

Plume dynamics can differ greatly between nighttime and daytime. At night, fire combustion shifts toward smoldering and low-intensity flaming. Decreasing surface temperatures favor the development of a nocturnal surface inversion, a stable layer in the atmosphere that suppresses convective motion. The combination of less buoyant smoke and suppressed convection leads to smoke being trapped near the surface, resulting in degraded air quality and visibility. Simulations with PB-P (Achtmeier 2005) indicate that dispersion of the nonbuoyant nocturnal smoke is largely driven by drainage flows. As the land surface cools and forms a shallow layer of adjacent cool air, small pressure gradients develop, forcing the cooled air downslope. The cool air accumulates in valleys and either pools there or continues flowing down-valley, depending on the slope of the valley floor.

The risk associated with accidents due to impaired visibility at night is amplified under certain conditions. Under a nocturnal inversion, smoldering combustion releases water vapor and particulates that act as cloud condensation nuclei (Engelhart et al. 2012) into the atmosphere. This warm, moist, smoky air mixes with cooler ambient air to form a saturated or potentially supersaturated air mass often referred to as superfog (Achtmeier 2006). The combination of saturated to supersaturated conditions, with an abundance of cloud condensation nuclei particles, creates an air mass dominated by very small droplets that scatter light and can greatly reduce visibility.

A simple two-part model based on radiational cooling of the smoke air mass to its dewpoint temperature, and nongradient mixing of the smoke and ambient air masses, was developed to simulate superfog formation (Achtmeier 2008). The simulation showed that the liquid water content of the smoke–fog mixtures was much higher than for natural fog and smoke, and for fog flowing northward along drainages from a prescribed burn 3.2 km to the south of a highway. Bartolome et al. (2019) coupled a thermodynamic model similar to that of Achtmeier (2008) with a two-dimensional boundary-layer model, which describes transport and turbulent mixing processes that control the persistence of superfog as it disperses from a burned area. Boundary-layer growth predictions from the model were verified with laboratory experiments, describing superfog development for two events.

Drainage flows are driven by cooling of sloping terrain, and surface type and moisture content affect cooling rates, influencing pollutant dispersion. Vegetation and terrain heterogeneities alter atmospheric dispersion patterns that switch from



**Fig. 4.4** Fire hotspots and smoke over the Pacific Northwest region on September 5, 2017: **a** satellite imagery and **b** WRF-CMAQ  $\text{PM}_{2.5}$  simulation (Zou et al. 2019a)

non-Gaussian to near-Gaussian behavior as soil moisture increases (Wu et al. 2009). Land-cover heterogeneity (e.g., a mosaic of dry areas and wet areas) can produce complex patterns of differential heating that induce complex atmospheric circulations at meso- and microscales. These circulation patterns are primarily responsible for the development of non-Gaussian dispersion patterns. Soil and vegetation have the biggest effect on atmospheric dispersion in the nocturnal boundary layer.

## **4.2.4 Interactive Processes**

### **4.2.4.1 Terrain Interactions**

The effects of terrain heterogeneity on atmospheric and smoke plume dynamics have been examined extensively in both observational and numerical modeling studies. These studies have shown that atmospheric boundary-layer, tropospheric wind, temperature, and moisture fields are strongly influenced by surface-elevation variations, land–water boundaries, and land-use/land-cover patterns. Terrain-induced phenomena such as katabatic winds (i.e., drainage flows), anabatic winds, föhn and chinook winds, terrain channeling of flows, land/sea breezes, and urban heat islands affect how smoke from wildland fires is transported and dispersed (Liu et al. 2009; Sharples 2009; Lu et al. 2012; Kiefer et al. 2019; Miller et al. 2019). Many of these same phenomena can directly affect the spread of wildland fires across the landscape, which in turn affects when and where fire emissions for subsequent transport and dispersion occur (Clements 2011).

### **4.2.4.2 Canopy Interactions**

The behavior of wildland fires in forested environments and the associated dispersion of smoke through forest vegetation depends on local ambient, fire-induced, and canopy-induced meteorological conditions (Heilman et al. 2013; Strand et al. 2013; Mueller et al. 2014). Forest vegetation acts as a drag on ambient and fire-induced winds (Massman et al. 2017; Charney et al. 2019; Moon et al. 2019), and horizontal and vertical wind shear patterns are a source of turbulence generation (Kiefer et al. 2015; Heilman et al. 2017). Vegetation can also influence the lower atmospheric boundary-layer thermal environment, which determines the amount of turbulence generated or dissipated through buoyancy (Kiefer et al. 2015; Charney et al. 2019). Finally, vegetation can generate wake-generated turbulence and enhanced dissipation of turbulence as canopy elements break down flow eddies to smaller sizes.

Observational and modeling studies that assess the potential effects of fire–canopy–atmosphere interactions on smoke plume behavior conclude that:

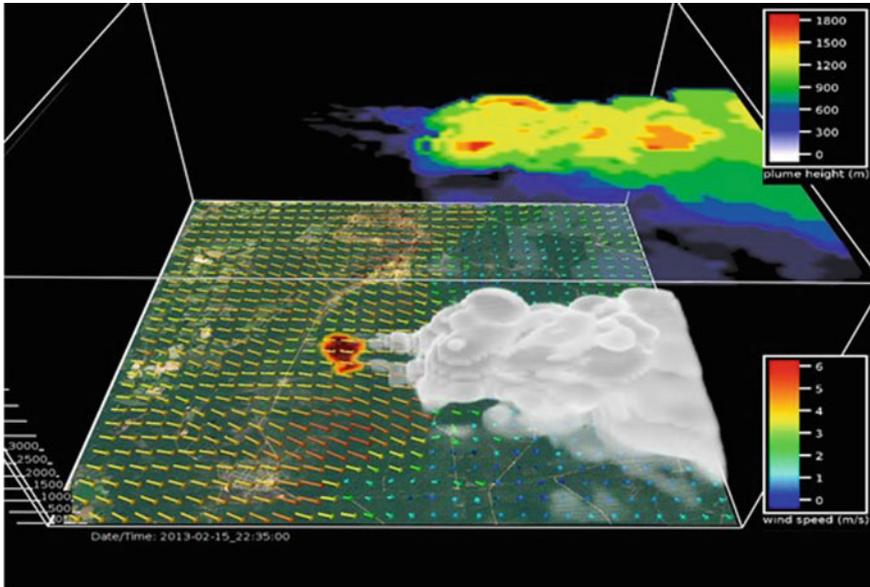
- Maximum increases in the energy of turbulent circulations as a result of fire spread can occur near the top of forest canopies, thereby enhancing the dispersion of smoke plumes (Heilman et al. 2015, 2019).
- Horizontal mixing of smoke plumes within forest vegetation layers due to turbulent circulations is often stronger than vertical mixing, particularly near the surface, both before and after the passage of fire fronts (Seto et al. 2013; Heilman et al. 2015, 2019).
- Distribution of turbulent velocity near wildland fires is highly skewed, making turbulence regimes in such environments non-Gaussian and calling into question the application of smoke modeling tools that assume Gaussian turbulence for diffusing smoke (Heilman et al. 2017).
- Dense forest canopies (high plant-area densities) can lead to more upright smoke plumes above and in the vicinity of combustion zones, corresponding with larger plume heights (Charney et al. 2019).

#### 4.2.4.3 Integrated and Interactive Systems

Several integrated and interactive systems of fire behavior, smoke, and meteorology are powerful tools for understanding the coupled processes linking smoke, fire, and the atmosphere, as well as informing different aspects of smoke management decision making. Although they operate on different scales and focus on different processes, FIRETEC (Linn and Cunningham 2005), WFDS (Mell et al. 2007), CAWFE (Coen 2013), Meso-NH ForeFire (Filippi et al. 2009), WRF-SFIRE (Mandel et al. 2011), and WRF-SFIRE-CHEM (e.g., Kochanski et al. 2015) are coupled models with the potential to resolve plume dynamics associated with fire behavior.

Physics-based computational fluid dynamics (CFD) fire models such as FIRETEC and WFDS have high spatial resolution (a few meters), requiring a large amount of computational resources. As a consequence, their use in wildfire-scale problems exceeding approximately 40 ha is not feasible. In an effort to improve fire and smoke modeling capabilities while maintaining modest computational cost and input requirements, so-called hybrid models have been developed. Models such as CAWFE, Meso-NH ForeFire, and WRF-SFIRE couple a CFD-type weather model with a simplified fire model to account for first-order fire–atmosphere interactions. Such models calculate plume rise and dispersion but rely on parameterized fire physics. As they treat smoke as a passive tracer, they can describe basic plume dynamics, but cannot account for interactions between smoke, atmospheric radiation, or chemistry. Efforts have been made toward developing integrated modeling systems that can take into account fire progression, emissions, plume rise, dispersion, and radiative and chemical impacts of smoke. For example, WRF-SFIRE-CHEM couples the chemical transport model WRF-CHEM (Grell et al. 2011) with the fire module SFIRE (Mandel et al. 2011).

In WRF-SFIRE-CHEM, a hybrid model that couples a CFD-type weather model with an empirical rather than a dynamical fire model, fire progression and emissions are driven by local meteorological and fuel conditions affected by fire itself, so the



**Fig. 4.5** WRF-SFIRE simulation of a prescribed burn at Fort Stewart, Georgia, on February 15, 2013. The color arrows represent wind speed (see right-hand color bar) and direction. The upper-level plane shows local plume heights (see right-hand color bar). From Liu et al. (2019)

fire progression is simulated in-line with fire emissions and chemistry. WRF-SFIRE-CHEM computes fire emissions and plume rise based on fire behavior, fuel moisture, and atmospheric conditions computed at each WRF time step (Fig. 4.5). Combustion rates are based on the mass of fuel consumed within each fire-grid point. Emission fluxes are the products of combustion rates and fuel-specific emission factors. Smoke emissions are represented as a sum of fluxes of chemical species and incorporated into the lowest WRF model layer. Smoke emissions are transported and undergo chemical transformations in the atmosphere according to modeled chemical mechanisms. Aerosol emissions are linked to the aerosol model (GOCART) and interact with atmospheric radiation and microphysics. Initial wildfire simulations suggest that WRF-SFIRE-CHEM can simulate elevated concentrations of  $\text{NO}_x$  and  $\text{PM}_{2.5}$  of fire emissions associated with wildland fires (Kochanski et al. 2015) (Fig. 4.5).

#### 4.2.4.4 Smoke–Radiation Interactions

The opacity of smoke from large fires affects solar irradiance as well as within-plume radiative transfer characterizations. Both gas and aerosol species contribute to this opacity and vary dynamically within the fire plume due to ongoing chemistry and aerosol physics after emission. Activation (or suppression) of clouds due to smoke can further complicate the understanding of smoke transport (Feingold et al. 2005).

Several sources of information are used to evaluate links between smoke properties and plume dynamics, including: (1) episodic collection of in situ gas and aerosol concentrations and the aerosol optical properties of smoke in different atmospheric regimes (e.g., Forrister et al. 2015; Liu et al. 2016; Selimovic et al. 2017; Ditas et al. 2018), (2) remote sensing of properties of large-scale burning pollution from satellite instrumentation, and (3) ground-based sun photometer and Lidar networks (e.g., Nikonovas et al. 2017). This information is incorporated into models via parametric simplifications and/or prescribed aerosol optical properties.

Numerical experiments have examined the local effects of smoke in complex terrain using an integrated framework coupled with the fire, atmosphere, and chemical transport model WRF-SFIRE-CHEM (Kochanski et al. 2015). Mallia et al. (2020) investigated smoke transport driven by small-scale topographical flows in a local wildfire event in Utah and found good agreement between simulated and observed spatial  $PM_{2.5}$  patterns, including realistic representation of the drainage flow advecting smoke into a valley.

Simulations of the 2015 California fires that included the radiative impact of smoke successfully resolved local reductions in incoming solar radiation and surface temperatures associated with smoke shading. Additional sensitivity experiments demonstrated a positive feedback associated with radiative smoke effects: smoke cools the surface, stabilizes the atmosphere, and enhances local inversions, as well as reducing the planetary boundary-layer height and near-surface winds, leading to reduced ventilation and smoke accumulation. This radiatively driven mechanism results in positive feedback, manifesting a nonlinear increase in surface  $PM_{2.5}$  concentrations as a function of increasing emissions (Kochanski et al. 2019).

#### 4.2.4.5 Smoke–Fire Interactions

Plume dynamics are directly linked to fire behavior because fire-emitted heat and moisture fluxes control the development of the buoyant smoke column. Conversely, the lack of fire-emitted heat results in surface-smoke accumulation and limited dilution, as often observed during fires in the Southeast. As a consequence, changes in fireline intensity affect plume buoyancy and evolution of the smoke column. However, fire behavior is linked to atmospheric conditions via coupling at various timescales. At scales of seconds to minutes, the most important atmospheric driver is wind, which drives fire propagation and controls the tilt and dispersion of the smoke column.

Fire also modifies local weather conditions. Pyroconvective plumes generate indrafts into the base of rising smoke columns, accelerating winds in the vicinity of the fire front. Observational data (Heilman et al. 2015; Clements et al. 2019) and numerical experiments (Kochanski et al. 2013a; Kiefer et al. 2014) have shown that fire-affected winds may be over two times stronger than ambient winds. These perturbations in near-surface winds that control heat release also depend on atmospheric stability and vertical wind shear (Kochanski et al. 2013b). Just as fire behavior is controlled by two-way coupling between fire and the atmosphere, so is plume dynamics.

### 4.2.5 *Smoke Decision Support Systems*

Decision support systems for smoke management consist of one or more computer-based applications that assist managers in planning for and implementing prescribed fires and can predict potential downwind impacts from wildfires. For example, a user interface developed for personal computers (<https://webcam.srs.fs.fed.us/tools/vsmoke>) allows the VSMOKE atmospheric dispersion model to estimate the maximum hourly  $PM_{2.5}$  and carbon monoxide, along with corresponding heat release rate (Anderson et al. 2004). A web-based version called VSMOKE-GIS displays a Google Map and results using the air quality index (see <http://weather.gfc.state.ga.us/GoogleVsmoke/vsmoke-Good2.html>).

The HYSPLIT trajectory model estimates downwind air quality impacts, facilitating an assessment of whether to implement a prescribed fire within ~2 days. Smoke management personnel typically use one of two decision support systems that utilize HYSPLIT. The first version uses the same user interface as VSMOKE, but the user interface also formats the Fire Emission Production Simulator (FEPS) (Anderson et al. 2004) hourly  $PM_{2.5}$  emission and plume rise estimates to produce the input files needed by PC HYSPLIT. The second version using HYSPLIT is the BlueSky Playground modeling framework (Larkin et al. 2009), which is used in the Montana–Idaho Airshed Coordinating Group’s decision support system. On the Internet, a user completes the inputs and runs the Fuels and Fire Tools (which includes FEPS) to estimate  $PM_{2.5}$  emission and plume rise, prior to running HYSPLIT. Both the BlueSky framework and the PC HYSPLIT version produce outputs that are viewed in Google Earth. BlueSky displays estimated  $PM_{2.5}$  concentrations, whereas PC HYSPLIT displays hourly results using an air quality index.

Resource managers use VSMOKE and HYSPLIT to assess potential smoke impacts during the daytime. PB-P, a web-based application (<https://piedmont.dri.edu>), is used to evaluate the flow of nighttime smoke and whether fog may form but requires field evaluations to earn confidence in its predictions. Users are encouraged to support decisions by obtaining spot weather forecasts within 5 km of the burn for certain weather and dispersion conditions (Long et al. 2014). If PB-P results and/or most of the conditions indicate potential for fog formation on roadways, then mitigation measures can be implemented.

Aside from the models outlined above, significant effort has been made toward operational implementation of hybrid fire–atmosphere models for integrated fire spread and smoke forecasting. Recent implementations of such models (Jimenez et al. 2018; Giannaros et al. 2020) have a potential to improve operational smoke forecasting by linking fire and smoke modeling. This type of system can simplify using coupled models for smoke forecasting by utilizing simple web portals for easy model initialization and online presentation of model results (Mandel et al. 2019).

## 4.3 Gaps in Understanding Plume Dynamics

### 4.3.1 *Measurements*

Although there have been various observations of plume structures during prescribed fires (Liu et al. 2012; Clements and Seto 2015; Clements et al. 2019), few observations exist for deep plumes from large wildfires. An exception is the Rapid Deployments to Wildfires Experiment (4.2.2.1; Clements et al. 2018), which sampled 22 wildfire plumes using a mobile Doppler Lidar (Clements and Oliphant 2014). Although this study sampled different wildfires, it was limited by a lack of real-time fire behavior observations.

There is an operational and research need for coincident measurement of fire, smoke, and atmospheric structures to better understand fire–atmosphere interactions and plume dynamics. To date, no datasets link airborne infrared imagery of fire-front properties (e.g., flame intensity and length, front spread rate, heat release) to vertical velocities, so our understanding of plume structures and what happens on the ground is limited. Direct measurements of vertical velocities in deep wildfire plumes, which are needed to better constrain modeled smoke injection heights and dispersion, are limited to one study (Clements et al. 2018).

Our understanding of deep wildfire plumes is also affected by having few observations of the microphysical properties of plume particles. These observations require in situ airborne sampling and/or remote sensing measurements, using dual-polarized Doppler radars. McCarthy et al. (2018) documented the dual-polarized features associated with bushfires in Australia, showing that the correlation coefficient is a potential indicator for ash and debris detection. Observational studies are needed using multi-wavelength radars to better understand the size and distribution of pyrometeors (large debris lofted above wildfires that are composed of the by-products of combustion of the fuels) in wildfire plumes. Furthermore, to better understand plume dynamics and their effects on fire behavior, a coordinated meteorological field program utilizing ground-based and airborne remote sensing and in situ sampling technologies targeting large, active wildfires is needed.

### 4.3.2 *Plume Rise*

Modeling of smoke plume rise has been evaluated primarily with multiple-angle satellite products. Although many tools have been developed for plume-rise modeling, less attention has been paid to modeling of vertical concentration profiles. Smoke profiles are generally specified, rather than resolved, based on fire dynamics and local weather conditions.

Smoke measurements have indicated the existence of multiple, simultaneous updrafts within a smoke plume. Multiple-core updrafts have smaller updraft velocities and diameters and are more affected by entrainment than single-core updrafts,

so they are less efficient in vertical smoke movement (Achtmeier et al. 2012). The number of updraft cores is a critical factor for describing plume rise (Liu et al. 2010). Some models have developed parameterization to include multiple core numbers in heat flux calculations or explicitly simulate multiple plumes. However, additional progress is needed in: (1) quantifying updraft; (2) understanding contributing factors for ignition patterns, vegetation structure, fire spread, and atmospheric processes; and (3) understanding the evolution of updrafts in the atmosphere (including mergence).

### ***4.3.3 Dispersion and Transport Modeling***

Although the fundamental science governing atmospheric transport and dispersion is fairly well-established in most smoke models, the evolution of strongly buoyant smoke plumes is poorly described (Goodrick et al. 2013). Therefore, simpler approximation schemes on coarser scales (e.g., WFDS-Level Set and WRF-SFIRE) are used (Ottmar et al. 2017). This is due in part to a lack of computational capacity, especially for operational purposes, but measurements are also lacking for key inputs of fuels, fire, and meteorology to support plume model development.

The successful evaluation and validation of modeling tools depend on availability of observational data across a wide range of spatial and temporal scales. Closing the gaps in our understanding of plume dynamics, transport, and dispersion is contingent on establishing new observational datasets upon which models can be evaluated and model output can be verified. Without ample observational data collected during actual wildland fire events or in controlled laboratory environments, the uncertainty and errors in model simulations of plume dynamics, transport, and dispersion are difficult to quantify.

### ***4.3.4 Nighttime Smoke***

Vertical and horizontal resolution is the primary challenge for modeling nighttime smoke drainage and potential superfog conditions. As large-scale forcing from synoptic weather systems weakens, details of the local environment are increasingly important. Tools such as PB-P account for the influence of local topography by using digital elevation models to resolve topographic variations at a horizontal grid size of 30 m. Although greater topographic resolution is needed to simulate drainage flows, a less obvious need includes land-cover types and surface-moisture conditions (micrometeorology).

### **4.3.5 *Physics-Based Fire Models***

As stated in Sect. 4.2.4.3, physics-based CFD fire models such as FIRETEC and WFDS can resolve the complexities of coupling fire dynamics with atmospheric dynamics; however, their computational costs and input data requirements make operational applications infeasible. Because these models focus on small-scale processes important from the combustion standpoint, they lack capabilities in terms of aerosol physics, microphysics, and chemistry which become important at the larger scales typical for wildland fires.

### **4.3.6 *Smoke Management for Prescribed Fires***

Managing smoke from prescribed fires requires technical specialists to work with fire managers to predict and effectively communicate likely smoke effects (Chaps. 7, 8). Occasionally, when a prescribed fire is conducted using mass ignition and no local smoke impacts are predicted or reported, the burn manager will be surprised to receive complaints of smoke from a location far downwind of the burn unit. Without implementing smoke prediction, it is hard to know how high the plume will rise and if fine particulates will travel a long distance from the fire. To effectively implement smoke prediction, we need to understand the strengths and weaknesses of smoke models, which are listed in NWCG (2020). In addition, managers need to be able to estimate multiple emissions and plume rise from co-occurring fires which will require input from both empirical data and model output.

## **4.4 Vision for Improving Plume Dynamics Science**

Both conceptual understanding and practical ability to accurately model wildland fire plumes are poised to make significant advancements. Improvements will be driven by a combination of increasing computing power, new observational techniques, new integrated observational campaigns, and greater recognition of the need for such improvements. We discuss these factors below and provide a vision for improving smoke plume research as a component of a broader perspective for fire and smoke science (Chaps. 2, 3, 5, 6, 7).

### ***4.4.1 New Research on Observational and Computational Capabilities***

Routine observations of plumes are currently limited to satellite observations of plume tops, with the longest time series coming from the polar-orbiting MISR (Diner et al. 1998) stereo imaging instrument. MISR is capable of imaging significant portions of the globe once per day, but the overflight time may not be optimal in terms of obtaining maximum plume height. The polar-orbiting CALIOP (Hunt et al. 2009) satellite Lidar system provides a vertically distributed glimpse into smoke plumes that fall directly under its orbital path. However, such observations are limited and often do not intersect the plume directly over the fire, further limiting their usefulness. The MISR twin satellite system and CALIOP Lidar capabilities are highly specialized and serve as research technologies, with operational capability still unavailable.

A new methodology (Lyapustin et al. 2019) for determining plume heights directly from aerosol and gas products of the Moderate Resolution Imaging Spectroradiometer (MODIS) (Justice et al. 2002, 2010) has the potential to make plume-top observations more routine. MODIS is based on two polar-orbiting satellites, and if it is applicable to other platforms, it could lead to operational implementation. A major advance in observing the development and evolution of plumes is possible if this technology can be applied to the new geostationary GOES-16 and GOES-17 (Schmidt 2020) Advanced Baseline Imager (ABI) (Schmit et al. 2005, 2008, 2017) imagery. Specifically, GOES-16 and GOES-17 provide imagery rapidly, and application of such a system to these platforms may allow for observation of plume-top development every 5 min throughout the day (perhaps every minute in some cases). This type of near real-time series observation on a routine basis would provide more than an order of magnitude additional observations of plume tops than are currently available, providing insight on how the plume is changing over short time intervals.

NASA is launching new missions to increase the capacity to detect air pollutants from different sources, including wildfires. The Multi-Angle Imager for Aerosols (MAIA) mission (<https://maia.jpl.nasa.gov>) is focused on understanding how different types of pollutants affect human health. The MAIA mission will study 12 specific locations in the world with dense population, available health records, and available ground-based air monitor data. Two of the locations, Los Angeles and Atlanta, are often affected by smoke, from wildfires and prescribed burns, respectively. The multi-angle data are useful for determining smoke plume heights. MAIA will pass over a specific location once a day in late morning. Another mission, Tropospheric Emissions: Monitoring of Pollution (TEMPO) (<http://tempo.si.edu>), will measure particles and gases in the troposphere (lowest layer of the atmosphere), but at an hourly frequency.

Planning for FASMEE (Prichard et al. 2019) has identified a comprehensive set of observations that could be obtained through large-scale planned burns (Liu et al. 2019). It may be possible to use multiple synchronized ground Lidar units with their directional measurements intersecting at a fire; the intersection would provide

a virtual vertical tower providing details on the movement of air and aerosols at the center of the plume. This capability is planned for future FASMEE burns.

Some citizen-science efforts have contributed to knowledge about plume dynamics, including a project in Canada that used trained volunteers with equipment to measure plume heights. However, newer technology may make such data easier to obtain and available in greater quantities. Cellphones can take photographs or video with high resolution and record the geolocation of the phone, so it is conceivable that an app would allow citizen scientists or agency personnel to quickly and accurately collect numerous photos. This type of image database would provide the potential to develop novel analytical techniques, using automated algorithms or distributed human-powered image interpretation.

As advanced models of plumes require substantial computing power, current coupled CFD-based models run too slowly for operational and decision support. Cloud computing and improved computer processing may allow advanced models to become practical for applications, either directly or in optimized variants. It is also possible that the vertical distribution of emissions can be reduced to a number of typical structures that could be derived from CFD modeling efforts, then related back to simpler quantities for faster application. Combinations of atmospheric profile, fuelbed type and conditions (e.g., moisture), fire size, fire shape, and regional topography may control the type of vertical allotment sufficiently that the cached results may be used within a smoke forecasting system, without the need to perform a new run of the full CFD model.

#### ***4.4.2 New Approaches and Tools***

Any effort to substantially improve our understanding of fire plumes needs to be multidisciplinary and integrated across modeling and field research. Incorporation of modelers and preliminary model results into the planning of observational campaigns that can help pinpoint areas where observations are most critical and ensure that time and space scales and resolutions of the observations are in sync with model analysis and development. The Department of Defense Strategic Environmental Research and Development Program field campaigns exemplify how to apply this approach for program-level direction and support. This includes forming an Integrated Research Management Team to coordinate/facilitate research integration and to act as an interface/liason between the host unit and researchers.

A set of intensively observed fires and a more limited set of broadly obtained observations are needed to inform our understanding of plume dynamics. This is similar to how fuelbed maps have been developed, with intensively measured specific plots combined with satellite observations to apply the plot observations across the map (Chap. 2). However, applications are needed on a scale of at least an order of magnitude more complex than what is used in creating fuelbed maps. Because spatial variability of fuels affects smoke plumes, fuelbeds will need to include appropriate spatial statistics (e.g., spacing between areas of higher or lower fuel density).

### **4.4.3 *New Projects***

Flexibility by agencies, institutions, researchers, and resource managers can help to facilitate timely advances. A good example is the initial planning stages of the FASMEE project (Ottmar et al. 2017; Liu et al 2019; Prichard et al 2019), which has incorporated modelers and observational lists from a wide range of research groups. Coordination among the FASMEE effort (Joint Fire Science Program), the FIREX-AQ aircraft campaign (NOAA, NASA), and the WE-CAN project (National Science Foundation) has demonstrated interagency and funding collaboration. FASMEE has provided ground-based observations in support of the FIREX-AQ Western wildfire aircraft campaign, and FIREX-AQ conducted detailed airborne observations of a prescribed burn in Florida.

The FIREX-AQ and WE-CAN experiments have produced observations that will allow researchers to analyze and improve the representation of smoke chemistry for the next several years (Chap. 6). FASMEE has produced an initial set of observations from two prescribed burns, with additional burns planned in coming years. The FASMEE observations are just beginning, and there is ongoing discussion for continued interagency collaboration on future burns.

New and developing efforts on the operational side have the potential to produce more data for model development. Specifically, deployment of Air Resource Advisors (ARAs) to wildfires under the Interagency Wildland Fire Air Quality Response Program (IWFAQRP) (Chap. 8; Lahm and Larkin 2020) has the potential to collect and aggregate operational fire information available to the assigned Incident Command Teams that can be used for retrospective studies. For instance, ARAs may be able to collect photographs of plumes and record requisite metadata. Datasets and tools developed for real-time distribution through the IWFAQRP are providing particulate monitoring data from permanent in situ networks and temporary monitors, including monitors deployed by ARAs that could be guided, in part, by the needs of smoke and plume model evaluation.

### **4.4.4 *Recent Policies and Integration with Smoke Impacts Research***

The National Cohesive Wildland Fire Management Strategy initiated in 2009 facilitates collaboration among stakeholders and across ecosystems in the USA to utilize the best science to address socially relevant wildland fire issues. The strategy focuses on resilient landscapes, fire-adapted communities, and safe and effective wildfire response. Plume dynamics and the interface of the fire environment are critical to all three goals. The USDA Shared Stewardship Strategy also provides impetus for improved knowledge about plume dynamics, recognizing that partnerships with states and private landowners are needed to address the problem of elevated fuels in fire-prone landscapes.

The plume dynamics portion of smoke science will contribute to the effectiveness of these strategies as smoke increasingly affects a range of critical social values (Chap. 7). Understanding the intersection of the physics of plume development with subsequent dispersion is needed to accurately predict air pollution and human health effects on the public and firefighters. Plume impacts and chemical constituents are critical for understanding air pollution and human health impacts, but the influence of complex chemistry and atmospheric conditions is also tied to visibility concerns. Smoke can be a contributing factor in roadway accidents, and accurate predictions of the location of smoke impacts are critical. With the recent increase in the use of prescribed fire and area burned by wildfire, more smoke-related incidents are expected, meaning that better information is needed on low-level plume movement, fumigation, and subsidence.

Recent research is helping to improve understanding of plume dynamics and must be integrated into operational tools that can be accessed and supported by ARAs, meteorologists, air quality specialists, prescribed fire practitioners, public health specialists, and policy makers. In addition to research needs, investment is also needed for validation and operational testing that can lead to applications.

Authorization of the IWFAQRP and use of ARAs on wildfire incidents to predict public health impacts of smoke are an example of how scientific information can address policy issues. Since the 1980s, some states have recognized the need to solve smoke issues and have implemented States Implementation Plans that address smoke management and emission reduction. The Northwest Fire Summit of 2019 noted that potential deaths from wildfire smoke likely far exceed those directly caused by the wildfire itself, but opportunities to study wildland fire smoke and operational response have been rare. A better scientific understanding of the health impacts of smoke is needed by practitioners engaged in managing smoke and air quality.

## **4.5 Emerging Issues and Challenges**

### ***4.5.1 Coupled Modeling Systems***

There is an ongoing effort to develop high-resolution dynamical systems that can account for interactions among atmospheric processes, fire behavior, fire emissions, and smoke dynamics (Liu et al. 2019). Current fire–smoke–atmospheric models such as WRF-SFIRE-CHEM use the Rothermel fire spread model. The next-generation coupled model will use high-resolution dynamical fire models such as FIRETEC (Chap. 3). Development of next-generation smoke research and forecasting systems requires coordinated measurements across fuels, fire behavior and energy, smoke and meteorology, emissions, and chemistry. More powerful computation capacity will be needed to make the coupled systems practical for real-time, operational applications.

### ***4.5.2 Improving Modeling Tools with Field Campaign Data***

Comprehensive field research campaigns including FASMEE, FIREX-AQ, and WE-CAN for evaluation of smoke modeling tools will advance our understanding of the complex fire–atmosphere system. They will also help evaluate how well specific models perform under real-world applications, the level of model uncertainties, and which sources of uncertainty can be improved. The outcomes are expected to (1) improve scientific knowledge of the physically coupled fuels–fire–smoke–chemistry system; (2) develop exportable methodologies for measuring fuels for fire spread, fuel consumption, and fire emissions models; (3) develop insights on processes that drive the spatial organization of fire energy and emissions; (4) improve existing operational fire and smoke models; and (5) develop advanced models based on data collected on fuels, fire, meteorology, smoke plumes, and smoke chemistry.

### ***4.5.3 Real-Time Smoke Transport Modeling and Prediction***

Over the past 20 years, smoke from large wildfires has affected metropolitan areas of the western USA for extended periods and, in some cases, has been transported thousands of kilometers across North America (Navarro et al. 2016). Accurate predictions of smoke transport are needed to inform effective mitigation (e.g., reduce outdoor activities, close highways, acquire respirators) (Chap. 7). Real-time prediction of smoke transport is critical (O’Neill et al. 2019) and can be assisted by dynamical coupled smoke modeling systems.

NOAA continues to improve its hazard mapping system with the latest fire and smoke monitoring methods and satellite data ([www.usfa.fema.gov/operations/infograms/011421.html](http://www.usfa.fema.gov/operations/infograms/011421.html)). The product provides near real-time maps, fire data statistics, and datasets for monitoring wildfire and smoke positions. The NOAA High-Resolution Rapid Refresh-Smoke (HRRR-Smoke) produces a new weather and smoke forecast every hour.

### ***4.5.4 Smoke from Duff Burning Under Drought Conditions***

It is typically difficult to burn duff (the layer of decomposing organic materials lying below the litter layer of freshly fallen twigs, needles, and leaves and immediately above the mineral soil) because of high fuel moisture (Varner et al. 2009; Ottmar 2014). However, under persistent drought conditions, duff will burn readily. Most of the deep duff layer was burned in the 2016 Rough Ridge fire in northern Georgia, which contributed to unexpectedly high fire emissions that dispersed into metro Atlanta (Zhao et al. 2019). Current tools likely underestimate duff in some regions. Better quantification of the duff layer is needed for accurate prediction of emissions as

well as for peat soils (Chap. 2), which have contributed to globally significant smoke events in terms of public health, climate, and regional air quality (Watts 2013).

#### ***4.5.5 Smoke Plume Dynamics and Climate Change***

Increasing drought associated with climate change will increase wildfire occurrence and emissions, affecting smoke dynamics. Ford et al. (2018) simulated the impacts of climate change on air quality, visibility, and premature deaths, concluding that fire-related PM<sub>2.5</sub> would increase in the middle and late twenty-first century. Altered atmospheric thermal structure, winds, and precipitation as a result of climate change could also affect smoke dynamics. For example, fuel moisture is projected to decrease in most US regions (Liu 2017), leading to more heat release from fires. Warming due to the greenhouse effect is larger on the ground than in the atmosphere, which will reduce atmospheric stability (Tang et al. 2015). Changes in both heat release and stability will allow smoke plumes to rise to higher elevations.

#### ***4.5.6 Smoke Dynamics in the Earth System***

Fire, smoke, ecosystems, and climate are interactive components of the Earth system (Bowman et al. 2009; Andela et al. 2017; Liu 2018). Smoke–climate interactions have long been part of climate modeling, which has shown that the radiative effects of some particles can affect: (1) Hadley circulation and precipitation in the tropics (Allen et al. 2012; Tosca et al. 2015), (2) regional climate and weather patterns in the middle latitudes (e.g., Grell et al. 2011), and (3) radiation–ice–temperature feedbacks in the polar region (Keegan et al. 2014; Winiger et al. 2016). Earth system models (Hurrell et al. 2013; Malavelle et al. 2019) include atmospheric models and dynamic global vegetation models to simulate environmental conditions for wildfires and atmospheric radiation and climatic effects of fire carbon and particle emissions and calculate fire-induced disturbances in land-cover and land–air fluxes. Earth system models have greater capacity for modeling interactions of wildland fires and smoke particles (Li et al. 2013, 2014; Unger and Yue 2014; Zou et al. 2019b). Improvements are needed to incorporate global fuel systems and provide dynamical fire emissions for smoke modeling and interactions with atmospheric processes.

### **4.6 Conclusions**

Large wildfires have increased in the USA, and smoke has degraded air quality and visibility in large areas. Recent advances in smoke measurements, model development, and operational decision support tools have increased our understanding

of smoke dynamics and ability to provide information to resource managers. Field campaigns focused on smoke–atmosphere interactions have revealed complex smoke structures and processes, and smoke-induced atmospheric disturbances and satellite imagery have been used to develop long-term global smoke plume height datasets. Integrated and interactive coupled models of smoke, fire, atmosphere, and canopies have been developed and applied to simulate smoke processes and mechanisms for air quality assessment, fire management, and climate change studies.

The largest gaps in smoke dynamics science are (1) the lack of high-resolution, dynamical fire, smoke, and atmospheric coupled systems; and (2) simultaneous measurements of these components, especially for wildfires. The following improvements are also needed:

- Smoke modeling needs to simulate buoyant dominant smoke processes.
- Integrated, multidisciplinary observational data across multiple temporal and spatial scales are needed to evaluate simulations of dynamical smoke processes and validate predictions.
- Improved methods are needed for modeling vertical plume distributions and multiple updrafts.
- The impacts of topography and the canopy on nighttime smoke need to be better described.
- Better predictions are needed for local smoke effects from prescribed fire.

Plume dynamics science is likely to improve through the development of new directions and strategies. New research directions include (1) increasing observational and computational abilities, using integrative tools with varied observation levels; (2) implementing field campaigns and operational management projects; and (3) implementing fire and stewardship strategies that help transition smoke dynamics science into operational tools for air quality and public health management.

## 4.7 Key Findings

- The focus of field experiments has changed recently from fire behavior to smoke–atmosphere interactions. Measurement techniques such as mobile atmospheric profiling systems equipped with scanning Doppler Lidar have revealed complex smoke structure and processes and smoke-induced atmospheric disturbances.
- Multiple-year smoke plume height datasets with regional and global coverages have been developed based on satellite multiple-angle detection and other techniques. The datasets are valuable for modeling some impacts and fire–climate interactions.
- A major advance in smoke modeling has been the development and application of integrated and interactive coupled models of smoke, fire, atmosphere, and canopy; smoke operational and decision support systems; and plume-rise models for wildland fires.

- Applications of these models have improved our understanding of smoke processes and mechanisms, such as factors determining plume evolution, feedbacks to ambient conditions, impacts of multiple updrafts on fire energy and plume rise, and formation of superfog. Modeling tools also provide concentrations and spatial and temporal distributions of emissions from wildland fire for air quality assessment and fire management.
- Recent improvements in our understanding of smoke dynamics include development of high-resolution dynamical coupled smoke research and forecast systems, smoke model evaluation and improvement using data from field campaigns, real-time smoke prediction, consideration of smoke from duff burning, and assessments of future smoke dynamics with respect to changing climate and the Earth system.
- Gaps in research on smoke plume dynamics can be specifically addressed through enhanced measurements of wildfire smoke, model improvement of buoyant dominant lines, model evolution using observational data across large spatial and temporal scales, development of vertical plume distributions, description of multiple updrafts, better description of how topography and canopy affect night smoke, and improvements in smoke predictions for prescribed fire.
- Plume dynamics science will generally improve through new research on observational capabilities and computational ability, new approaches and tools of integration, varied levels of observations, new partnerships, and new field campaigns. These will help transition smoke dynamics science into operational tools for air quality and public health management.

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