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Review

Modelling smoke transport from wildland fires: a review

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Abstract. Among the key issues in smoke management is predicting the magnitude and location of smoke effects. These vary in severity from hazardous (acute health conditions and drastic visibility impairment to transportation) to nuisance (regional haze), and occur across a range of scales (local to continental). Over the years a variety of tools have been developed to aid in predicting smoke effects. This review follows the development of these tools, from various indices and simple screening models to complex air quality modelling systems, with a focus on how each tool represents key processes involved in smoke transport.

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Introduction

Smoke is an aspect of wildland fire where effects can cover a broad range of temporal and spatial scales. Smoke effects can range from short duration events with high concentrations that can significantly affect human health (such as for the fires in Southern California; Clinton *et al.* 2006), to long duration events that immerse a region in a low but constant background level of smoke with intermittent spikes of high concentrations over a period of weeks to months (Strand *et al.* 2011). At the local scale, potential reductions in visibility due to smoke present significant roadway hazards, providing an additional threat to human safety (Mobley 1989). At broader scales smoke can affect regional air quality (Meagher *et al.* 1998) as well as regional climate (Liu 2005). In addition, smoke-related degradation of air quality and visibility hazards are among the most negative effects of prescribed burning, an important land management practice (Ward and Hardy 1991; Sandberg *et al.* 1999; Riebau and Fox 2001). Land managers must balance issues of human health, nuisance smoke, visibility impairment and transportation hazard with issues of forest health and safety, wildlife management, ecosystem restoration, timber production and carbon sequestration (Achtemeier *et al.* 1998).

Models for predicting the smoke effects of wildland fires can consist of four basic components. The first component is a description of the emissions source, which should include both pollutants and heat release. The second component involves determination of plume rise through examination of the atmosphere's stability and wind profile as well as the fire-source rate of heat release to determine the vertical extent of the plume. The third component, which somewhat overlaps with the plume rise component, is the actual movement of the smoke (transport and dispersion) by the ambient wind. Although the fourth component may not be included in all smoke-modelling tools, a consideration of chemical transformations that occur as smoke constituents react with each other, and the ambient atmosphere, is essential for addressing a range of air quality issues, most notably ozone formation.

The effect on air quality of smoke from agricultural and forest burning has been a major research topic for many decades, not only in the United States but in many other countries around the world. During this period many methods to simulate and predict the transport and dispersion of smoke have been developed. This review examines models that have been used to simulate smoke transport and dispersion, with an emphasis on those tools being used operationally, or those that present significant advances in the state of the science. It is in no way intended to be an exhaustive review of air quality models. The review describes Box, Gaussian Plume, Lagrangian (puff and particle) and Eulerian grid models, as well as more complex models that use fewer assumptions to solve the momentums governing atmospheric transport. The review finishes by describing modelling frameworks.

Box models

A single box model is the simplest approach to estimating pollutant concentrations over a given domain (Lettau 1970). As the name implies, a box model assumes that an airshed can be represented by a simple box whose height is defined by the top of the mixed layer, and whose horizontal dimensions are defined by the spatial extent of the airshed. A key assumption in the box model is that emissions are instantaneously well-mixed throughout the entire volume of the box, bypassing the processes

Table 1. Interpreting Atmospheric Dispersion Index (ADI) values (Lavdas 1986)

ADI	Interpretation
>100	Very good, but may indicate hazardous burning conditions
61–100	Good
41–60	Generally good (Climatological afternoon values in most inland forested areas of the United States)
21–40	Fair (stagnation may be indicated if accompanied by persistent low wind speeds)
13–20	Generally poor for daytime conditions (stagnation), but above average values for nighttime
7–12	Poor, stagnant during the day, near to above average values for nighttime
1–6	Very poor (common at night, can represent majority of nights in many locations)

of plume rise and dispersion and treating the entire lower boundary of the box as the emission source. Reiquam (1970) did allow for horizontal transport by dividing the lower atmosphere into a series of boxes with a mean wind transporting pollutants from box to box.

One example of a box model used for smoke management is the Ventilated Valley Box Model or VALBOX (M. L. Sestak, W. E. Marlatt and A. R. Riebau, unpubl. data, 1988). VALBOX is a screening model designed to predict ground level concentrations of particulate matter and gaseous pollutants under stagnation conditions in mountain valleys. In this case the box is defined by the valley floor and sides, and an atmospheric inversion that restricts vertical mixing of smoke. Although VALBOX is not ideal for predicting surface concentrations from single fires, it is useful when assessing total smoke loading within a valley for an air quality episode that lasts several days (Brown and Bradshaw 1994).

The assumption that emissions are uniformly distributed within the box volume is very restrictive. Instantaneous mixing of pollutants requires that there be mechanisms such as diffusion, turbulent mixing, diurnal wind patterns and diurnal variations in mixing height that will accomplish this mixing throughout the box volume given sufficient time. With the spatial scale of a box representing an airshed, the time scale is often considered to be on the order of a day. Finer time resolution would require subdividing the airshed into smaller boxes, which increases the computational requirements of the model and loses the simplicity that is the primary advantage of the box model. Maintaining the simple description of an airshed limits box models to discussing air quality episodes that are predominantly multiple-day and often multiple-source events that affect a sizable area. Pharo *et al.* (1976) judged that a box model overestimated smoke concentrations within 100 km of the fire as a result of the instantaneous mixing assumption, because the combination of buoyancy and turbulent mixing tends to initially concentrate much of the plume mass near, or in some cases above, the top of the boundary layer, which then mixes down further downwind.

The simplicity of the box model is evident in an index commonly used to estimate the atmosphere's ability to disperse pollutants. The ventilation index (VI) is defined as the product of the mixing height and the mean wind speed through the mixing layer, also called transport wind speed. The transport wind speed and direction, mixing height and VI are routinely transmitted by the National Weather Service in its fire weather forecasts. The logic of the ventilation index is compelling. Therefore, it has come as an unexpected surprise that preliminary results from the Southeastern Smoke Project (G. L. Achtemeier, L. P. Naeher, J. Blake, J. Pierce, D. MacIntosh, unpubl. data, 2007) – a 5-year effort measuring fire activity data, concentrations of particulate matter up to 2.5 μm in diameter ($PM_{2.5}$) from a network of up to 22 samplers, and concurrent weather data for 56 prescribed burns – show little to no correlation between smoke concentrations and the VI. Similar to the results of Pharo *et al.* (1976), the near-field nature of the measurements by G. L. Achtemeier *et al.* (unpubl. data, 2007) suggest that VI is not an accurate predictor of smoke concentrations near the burn site, but it may become more accurate with increasing distance from the source as the smoke becomes better mixed throughout the depth of the mixing layer and better mimics the assumptions of the box model.

Another smoke management index with roots in the box model concept is the Atmospheric Dispersion Index (ADI) of Lavdas (1986). As with the VI, the primary inputs of the ADI are mixing height and transport wind, but the ADI also requires information on atmospheric stability as defined by Pasquill (1961, 1974). The ADI provides an open-ended scale for evaluating smoke dispersion conditions for both daytime and nighttime conditions (Table 1). Although higher values of either the VI or ADI reflect improved dispersion capacity in the atmosphere, this improved dispersion comes with an increased potential for erratic fire behaviour as a result of stronger winds, an unstable atmosphere or a combination of these factors (Lavdas 1986).

Box models represent an extreme simplification of the smoke dispersion process as they instantly disperse emissions uniformly throughout the box volume, eliminating the need for a description of plume rise or diffusion. Required meteorological data are reduced to know mixing height and transport wind speed, and these variables are assumed to be constant for a given box volume. Near a fire the assumption of instantaneous mixing cannot be met as the initial buoyancy of smoke tends to concentrate smoke closer to the top of the mixing layer. For this reason, concentration estimates from box models tend to be too high within 100 km of the fire. Box models can be instructive when trying to assess total pollutant load within an airshed.

Gaussian plume models

Compared with a box model, a plume model is a step towards a more realistic description of a smoke plume. Rather than treating a fire as a diffuse area source spread across an entire airshed, plume models define the source as a point or specific area encompassing the fire. Atmospheric processes of transport and dispersion are treated with greater detail than the instantaneous dispersion of a box model. Smoke is transported in the direction defined by a wind that is constant in both space and time. Crosswind dispersion is represented by a Gaussian distribution. Original applications for such models are rooted in industrial pollutant emission studies, but two wildland fire specific Gaussian plume models have been developed, namely

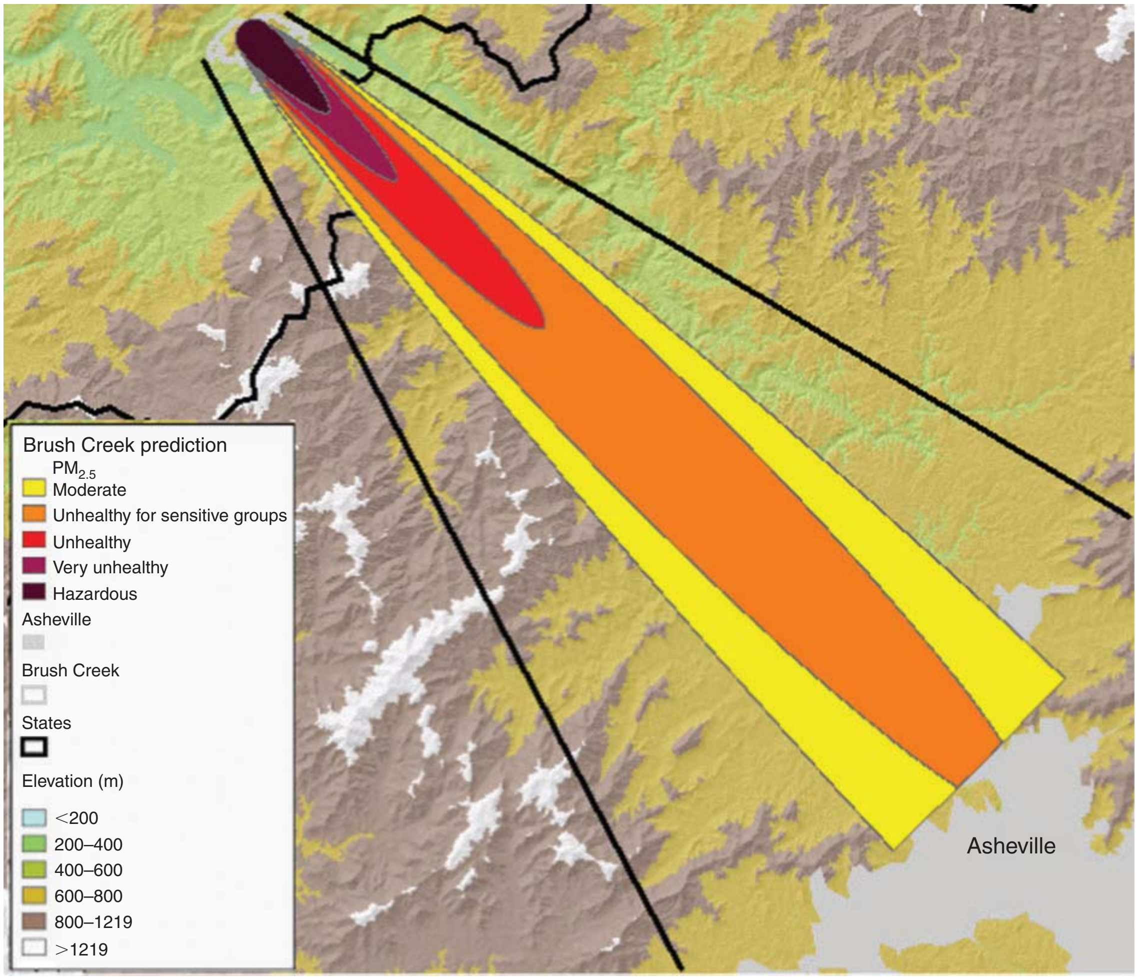

Fig. 1. VSMOKE predicted $PM_{2.5}$ concentration pattern for Brush Creek prescribed fire.

VSMOKE (Lavdas 1996) and SASEM (Sestak and Riebau 1988). These tools build upon Turner's (1970) Gaussian dispersion theory.

Fig. 1 shows an example of a VSMOKE simulated Gaussian $PM_{2.5}$ concentration pattern for the Brush Creek prescribed burn in eastern Tennessee on 18 March 2006 (Jackson *et al.* 2007). The plume spreads from the fire location in the upper left of Fig. 1 towards the lower right corner (south-east). As smoke is dispersed through a larger volume with distance downwind, mass conservation requires concentrations to drop. Therefore the highest concentrations of smoke and the greatest threat to air quality are found close to the location of the burn (dark maroon colours). VSMOKE gives land managers a quick and quick estimate of smoke effects given their planned fire activity and prevailing weather (mixing height, transport winds and atmospheric stability). VSMOKE is currently used as a smoke screening model for Forest Service applications in the Southeast (W. A. Jackson, 2008, pers. comm.).

Plume rise is not incorporated in VSMOKE. The user specifies a fraction of smoke that is released at the ground *v*. the amount released near the top of the mixing layer. Based on observations of prescribed fires in the south-eastern United States, Pharo *et al.* (1976) suggested partitioning the emissions with a ratio of 60% subject to plume rise and 40%, no-plume-rise. Although the assumption of all smoke being confined to the mixing layer is workable for small prescribed fires, plumes from large prescribed fires and wildfires do rise above the mixing height (Banta *et al.* 1992), sometimes by a several thousand metres. That means much fine particulate matter can be transported above the boundary layer and away from ground-level sensitive targets. VSMOKE's assumption that all smoke stays within the mixed layer limits its applicability in such cases and would strongly overestimate surface smoke concentrations.

SASEM (Simple Approach Smoke Estimation Model; Sestak and Riebau 1988) is another example of a plume model designed for use with wildland fires in flat to gently rolling terrain in the western United States. SASEM predicts ground-level particulate matter and visibility impairment from single fires and utilises internally calculated plume rise based on Briggs (1975), and emission rates based on specified fuel types. Like VSMOKE, SASEM is a screening model, in that it uses simplified assumptions (steady-state, homogenous weather and all smoke confined to mixed layer) and tends to overpredict effects, yielding conservative results. SASEM is used for prescribed fire planning in Arizona.

Gaussian plume models assume smoke travels in a straight line under steady-state, homogenous conditions. Areas of changing weather conditions such as approach and passage of frontal systems, or areas prone to local phenomena such as sea breezes or slope and valley winds in complex terrain, are likely to violate these assumptions and reduce the reliability of the results. One advantage of plume models is that they do not require detailed weather inputs and are very useful when meteorological information is scarce.

Puff models

The next class of dispersion models, puff models, relaxes many of the limiting assumptions of the Gaussian plume model. In a puff model, a smoke plume is represented as a collection of independent 'puffs' released throughout the duration of the burn with each 'puff' representing a volume that contains a specific amount of pollutant. With time, these puffs are transported by winds that vary in both space and time (and can include the influence of complex terrain). In addition, the puffs expand with time due to diffusion and entrainment. As the puff volume increases, the pollutant concentration decreases within the puff. Examples of puff models used for wildland fire applications include CALPUFF and HYSPLIT.

CALPUFF (Scire 2000) is a modelling system that consists of a diagnostic meteorological model (CALMET) and an advanced Lagrangian–Gaussian non-steady-state air quality model (CALPUFF). CALMET produces hourly fields of such meteorological parameters as winds, temperature, mixing height and plume dispersion on a three-dimensional gridded modelling domain by either interpolating routine surface and upper air meteorological data or downscaling output from a numerical weather prediction model such as The Fifth-Generation NCAR/Penn State Mesoscale Model (MM5) or by merging both together. CALPUFF is one of the US Environmental Protection Agency's (EPA) preferred models for assessing transport of pollutants and their effects, on a case-by-case basis, or for certain near-field applications involving complex meteorological conditions (Scire 2000). CALPUFF handles buoyant plume rise following the basic methodology of Briggs (1975), with a modification following Manins (1979) designed to estimate partial plume penetration above the top of the mixing layer.

Choi and Fernando (2007) applied CALPUFF in assessing the effect of smoke on air quality from agricultural fires in the San Luis–Rio Colorado airshed along the USA–Mexico border. The primary difficulty experienced during the study was finding and translating information on fire activity (such as the firing technique applied, fuel condition, time of burning) into suitable source inputs for CALPUFF. Jain *et al.* (2007) examined the effect of different methods for describing fires (area or line source) in CALPUFF and how the different methods influenced plume rise and surface smoke concentrations. Findings indicated that smoke plumes are complex entities that are not easily characterised for input into dispersion models, as different parts of a fire can have differing heat and emissions release rates that vary in both space and time. Additional applications of CALPUFF in the realm of wildland fire have included examinations of regional haze impairments in the north-western United States (McKenzie *et al.* 2006).

The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model (Draxler and Rolph 2003; Rolph 2003) is a complete system for computing simple air parcel trajectories and complex dispersion and deposition simulations. A joint effort between the United States National Oceanic and Atmospheric Administration (NOAA) and Australia's Bureau of Meteorology, the model has recently been upgraded to include modules for chemical transformations. As the name suggests, HYSPLIT uses a hybrid modelling approach, using either puffs, particles or a combination of these. In the puff model, puffs expand until they exceed the size of the meteorological grid cell (either horizontally or vertically) and then split into several new puffs, each with its share of the pollutant mass. In the particle model, a fixed number of initial particles are advected about the model domain by the combined mean and turbulent wind fields. The model's default configuration assumes a puff distribution in the horizontal and particle dispersion in the vertical direction. In this way, the greater accuracy of the vertical dispersion parameterisation of the particle model is combined with the computational efficiency of having an array of puffs represent the horizontal pollutant distribution. Currently, HYSPLIT does not account for plume rise as all puffs are assumed to have neutral buoyancy. The user can mimic buoyant plume rise by specifying the altitude of a release.

A Smoke Forecasting System (SFS) intended to provide air quality forecasters and the public with guidance on expected fine particulate matter ($PM_{2.5}$) concentration emitted from large wildfires and agricultural burning is currently operated by NOAA. The SFS integrates satellite-based fire detection products from the National Environmental Satellite, Data and Information Service (NESDIS) Hazard Mapping System (HMS), particulate matter emission rates from the USDA Forest Service's BlueSky Framework (Larkin *et al.* 2009), and dispersion calculations using HYSPLIT. Rolph *et al.* (2009) conducted a model evaluation comparing SFS predicted plumes with actual smoke detected from satellites by the HMS and the Geostationary Operational Environmental Satellite (GOES) Aerosol/Smoke Product. For the 2007 fire season (September 2006–November 2007) satellite-detected plume footprints tended to be smaller than the corresponding model plume footprints during the winter months, suggesting either that emissions for these fires were possibly overestimated, leading to an overprediction of the smoke area, or that the plume was getting placed in the wrong transport layer. In addition, the SFS uses an older version of the BlueSky Framework to estimate emissions; an updated version (ver. 3.1) is currently under review to replace ver. 2.0. NOAA's use of HYSPLIT for forecasting smoke concentrations can be traced to the extensive 1998 wildfires in Florida and Central America.

Puff models provide a significant step forward over Gaussian plume models as they can effectively deal with time-varying meteorological conditions and complex terrain, two limitations of plume models. One difficulty in applying puff models to wildland fires is adequately describing a fire as an emissions and heat source to accurately determine plume rise and the distribution of emissions throughout this depth. Puff models (as well as particle models) are capable of using time-varying emission sources, which allows for a more accurate representation of the ramp up, maximum combustion and ramp down phases of the burn. Timing of emissions production must match the diurnal evolution of the boundary layer depth so that the discharge of pollutants within and above the mixing layer can be accurately simulated.

Particle models

Although the ability of puff models to deal with flow fields that vary in space and time is a significant advance over plume models, their assumptions regarding the expansion of the puffs via parameterised diffusion and entrainment can be limiting in regions of strong turbulence or high levels of wind shear. In particle (or random walk) models there is no numerical diffusion of the pollutants. Each particle represents an infinitesimal air parcel containing a fixed mass of pollutant. Individual particles respond to the mean and turbulent components of the wind field, making diffusion a direct result of the movement of particles rather than a parameterised process. This more direct simulation of dispersion comes with significant computational costs as the number of particles required to represent the plume is often two to three orders of magnitude greater than the number of puffs. Pollutant concentrations are determined by examining the number of particles within a given volume. Thomson (1987) provides the basis for current atmospheric particle models, outlining the criteria for a model to be theoretically correct in this formulation. The theory of stochastic Lagrangian models was presented in a monograph by Rodean (1996) and another comprehensive review was written by Wilson and Sawford (1996).

For application to wildland fires, we examine three models: FLEXPART, DaySmoke and PB-Piedmont. Although FLEXPART follows traditional Lagrangian particle modelling theory, DaySmoke is an empirical model that employs particle modelling in a hybrid model formulation, and PB-Piedmont is a particle model adapted specifically to modelling the movement of residual smoke in a stable, nocturnal environment. The puff model HYSPLIT, described above, can also be run as a particle model.

FLEXPART (Stohl and Thomson 1999) is a Lagrangian particle dispersion model designed to simulate the long-range and mesoscale transport, diffusion, dry and wet deposition, and radioactive decay of tracers released from point, line, area or volume sources. Wotawa and Trainer (2000) utilised FLEXPART as part of an examination of the influence of Canadian forest fires on air quality in the south-eastern United States during the Southern Oxidants Study (Meagher *et al.* 1998). With FLEXPART, the variance in carbon monoxide estimates explained by the inclusion of fire emissions ranged from 52 to 64% and exceeded the variance explained by transport from anthropogenic sources. To account for plume rise in FLEXPART, Wotawa and Trainer (2000) assumed that fire emissions would be handled as an elevated source, evenly distributing fire emissions between 500 and 3000 m above the ground.

DaySmoke is an extension of ASHFALL, a model developed to simulate deposition of ash from sugarcane fires (Achtemeier 1998). As adapted for prescribed fire, DaySmoke consists of four sub-models: an entraining turret model, a detraining particle model, a large eddy parameterisation for the mixed boundary layer, and a relative emissions model that describes the emission history of the prescribed burn. The entraining turret model handles the convective lift phase of plume development and represents the updraft within a buoyant plume. This updraft is not constrained to remain within the mixed layer. A burn in DaySmoke may have multiple, simultaneous updrafts cores. In comparison with single-core updrafts, multiple-core updrafts have smaller updraft velocities, are smaller in diameter, are more affected by entrainment, and are therefore less efficient in the vertical transport of smoke. The importance of multiple-core updraft plumes is demonstrated with the Brush Creek prescribed burn in eastern Tennessee on 18 March 2006 (Jackson *et al.* 2007; Liu *et al.* 2010). This burn caused a smoke incident at Asheville, NC, ~50 km (30 miles) from the burn. The multiple-core updraft structure of the plume is shown in Fig. 2. Two updraft cores are easily visible in the image. An additional 1–3 updraft cores can be deduced from the shape of the surrounding plume. DaySmoke simulations with 1 to 10 updraft cores produced hourly $PM_{2.5}$ concentrations in Asheville ranging from 45 $\mu g\,m^{-3}$ (single updraft core) to 240 $\mu g\,m^{-3}$ (ten updraft cores). The simulation with four updraft cores produced an hourly peak $PM_{2.5}$ concentration of ~140 $\mu g\,m^{-3}$ at Asheville, which was the amount measured.

The majority of applications of dispersion models to wildland fire smoke focus on simulating the convective plume, often focussing on regional scale air quality concerns. However, a more deadly smoke effect in many regions, in terms of personal injury and lives lost, is from local smoke transport at night and reduced roadway visibility. Smoke entrapped near the ground in nocturnal inversions can drift into populated areas and affect residents, particularly those with respiratory problems. Smoke-laden air masses can drift across roadways and contribute to poor visibility. Smoke and associated fog has been implicated in multiple-car pile-ups that have caused numerous physical injuries, heavy property damage and fatalities (Mobley 1989). Planned Burn-Piedmont (PB-P) (Achtemeier 2005) is a very high resolution meteorological and smoke model that can be used predictively or diagnostically to simulate near-ground smoke transport at night over complex interlocking ridge-valley systems typical of landforms over much of the eastern United States. Fig. 3 shows part of a PB-P simulation for 0000 hours Central Standard Time (CST) 15 February 2011. The figure shows smoke and fog flowing northward following drainages that lead from a prescribed burn located ~3.2 km (2 miles) to the south of a highway in southern Mississippi.

Eulerian grid models

In contrast to the moving coordinate frame used by puff and particle models (often referred to as Lagrangian coordinates), grid models use a reference frame that is fixed in both space and time (Eulerian coordinates). The easiest way to conceptualise a grid model is to consider it as a collection of interconnected box models arranged as a regular lattice. Although the fixed coordinates make it difficult for grid models to track the effect of individual plumes, grid models are more practical for examining the cumulative effects from several plumes combined with

Fig. 2. Photograph showing plume core structure for Brush Creek prescribed fire.

anthropogenic emission sources. The structured grid also facilitates modelling chemical transformations that may occur as pollutants interact with both themselves and the environment. This makes grid models especially useful for evaluating the effect of smoke on regional haze and ozone.

The USA EPA Community Multiscale Air Quality (CMAQ) modelling system (Byun and Ching 1999; Byun and Schere 2006) is a third-generation air quality model designed for a wide range of applications covering regulatory and policy analysis as well as research questions concerning atmospheric chemistry and physics. CAMQ is a comprehensive atmospheric chemistry and transport modelling system capable of simulating ozone chemistry, particulate matter (PM), toxic airborne pollutants, visibility and acidic and nutrient pollutant species throughout the troposphere. A key feature of CMAQ is its 'one-atmosphere' model design philosophy that allows CMAQ to address the complex couplings among several air quality issues simultaneously across a range of spatial scales.

In addition to the work of Liu *et al.* (2010) mentioned above in relation to DaySmoke, CMAQ has been used for several wildland fire related air quality studies. Hu *et al.* (2008) used CMAQ to examine the effects on urban air quality from a pair of prescribed fires that affected Atlanta in February 2007. Lacking detailed information on the fire sources, emissions from the two prescribed fires were evenly distributed within the lowest 1 km of the atmosphere. Predicted peaks in $PM_{2.5}$ were lower than observed and their timing was delayed by 2–3 h. Ozone prediction fared far worse as the model responded with a broad, gradual rise in ozone and completely missed the sharp spike in the ozone observations that coincided with the fire induced $PM_{2.5}$ peak. The deficiency in the ozone predictions are likely tied to errors in the emissions of volatile organic compounds. Liu *et al.* (2009) examined the same event using CMAQ, but utilised DaySmoke for determining the vertical distribution of emissions rather than a uniform distribution. The change in vertical distribution of emissions improved the timing of predicted $PM_{2.5}$ peaks, and although the magnitudes were improved, they were still underestimated. Tian *et al.* (2008) employed CMAQ to investigate the effects on air quality of alternative land management plans by comparing changes in prescribed fire frequency.

Although CMAQ is widely used in the United States due to its connection with the EPA, it is not the only grid model to be used to examine wildland fire related effect on air quality. Hodzic *et al.* (2007) employed the CHIMERE model to examine the effect of particulate matter emissions during the summer of 2003 on air quality in Europe, and how the smoke altered the radiative properties of the atmosphere by producing a simulated 10 to 30% decrease in photolysis rates and an increase in atmospheric radiative forcing of 10–35 $W m^{-2}$ during the period of strong fire influence throughout a large part of the continent. These results suggest that wildfire events may have significant effects on regional photochemistry and atmospheric stability that need to be considered in chemistry-transport models. Christopher *et al.* (2009) examined air quality effects of the 2007 Georgia–Florida wildfires using satellite measurements to capture the spatial distribution and diurnal variability of columnar smoke aerosol optical depth and numerical simulations of the event using AERO-RAMS, a modified version of the Regional Atmospheric Modelling system (RAMS) mesoscale transport model with aerosols (Wang *et al.* 2006). Although AERO-RAMS succeeded in capturing the timing and location of aerosols, the simulated mass concentrations were underestimated by nearly 70%, when compared with observations. Possible sources of error include uncertainties in fire emission estimates, lack of chemistry in the model and assumptions on the initial vertical distribution of aerosols.

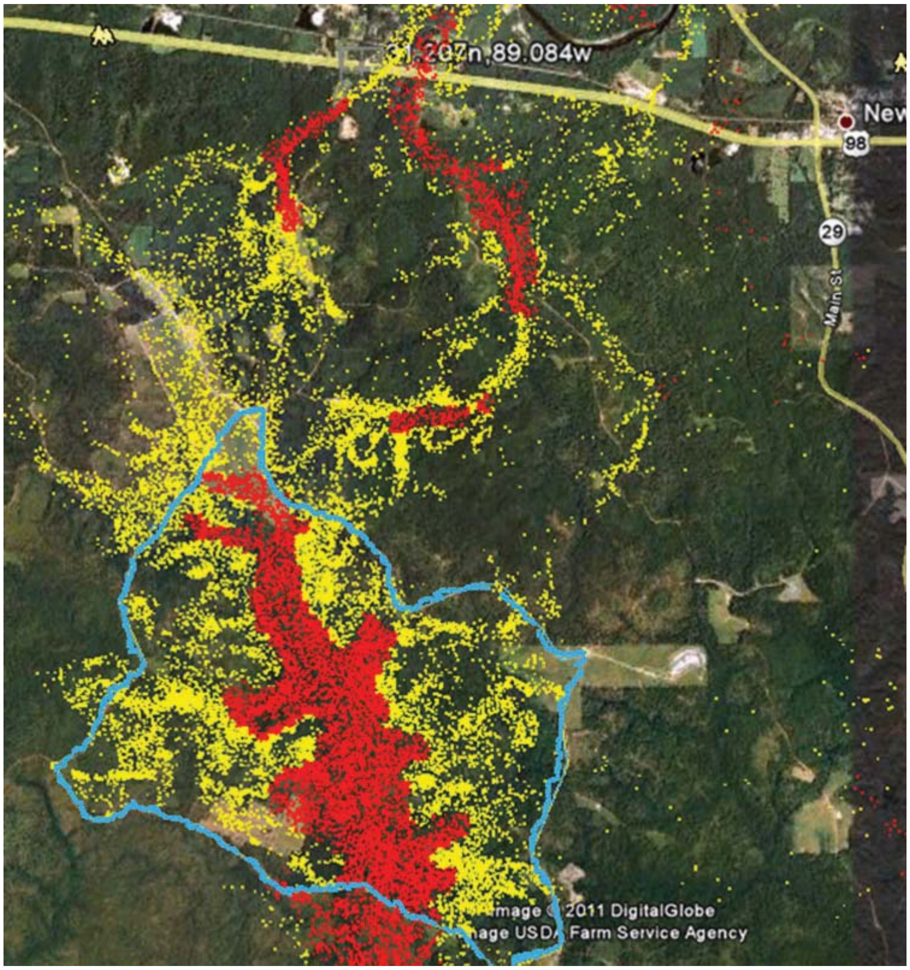

Fig. 3. Sample PB-P output for southern Mississippi showing predicted smoke and fog flowing northward from burn site (blue polygon) on 15 February 2012 at 0000 hours Central Standard Time. Yellow particles indicate smoke, whereas red particles are smoke and fog combined.

Another grid model receiving attention for wildland fire related air quality issues is the chemistry version of the Weather Research and Forecasting Model, WRF-Chem (Skamarock *et al.* 2005; Grell *et al.* 2005). WRF-Chem can simulate trace gases and particulates interactively with the meteorological fields, thus allowing the emissions to potentially influence the meteorology through radiative or cloud microphysical processes. Grell *et al.* (2010) found that fire emissions were capable of substantial weather modification in their examination of the effect of Alaskan wildfires on regional weather prediction. Changes in radiation induced by smoke aerosols produced significant modifications of vertical profiles of temperature and moisture in cloud-free areas. In cloudy areas, the high concentrations of fine aerosol ($PM_{2.5}$) and the resulting large numbers of cloud condensation nuclei (CCN) altered cloud processes in a manner that significantly changed the spatial distribution and intensity of precipitation events. A notable aspect of this study is the inclusion of a one dimensional cloud-resolving model designed to handle plume rise from wildland fires (Freitas *et al.* 2007).

A potential limitation of grid models, as with box models, is the assumption of instantaneous diffusion of emissions evenly throughout a grid volume. Although there is little that can be done to reduce this limitation with respect to horizontal diffusion, beyond reducing the model grid spacing to achieve finer resolution, the vertical distribution of emissions can be dramatically improved through the use of a plume in grid technique to more fully describe the plume rise process, as was done by Grell *et al.* (2010) and Liu *et al.* (2010). An emerging technique that balances the need for higher spatial resolution with their computational costs is the application of adaptive model grids within CMAQ (Odman *et al.* 2001; Garcia-Menendez *et al.* 2010). Adaptive grids dynamically change their resolution in response to environmental gradients; improving resolution in regions where conditions show sharp gradients and reducing resolution in regions of little variation.

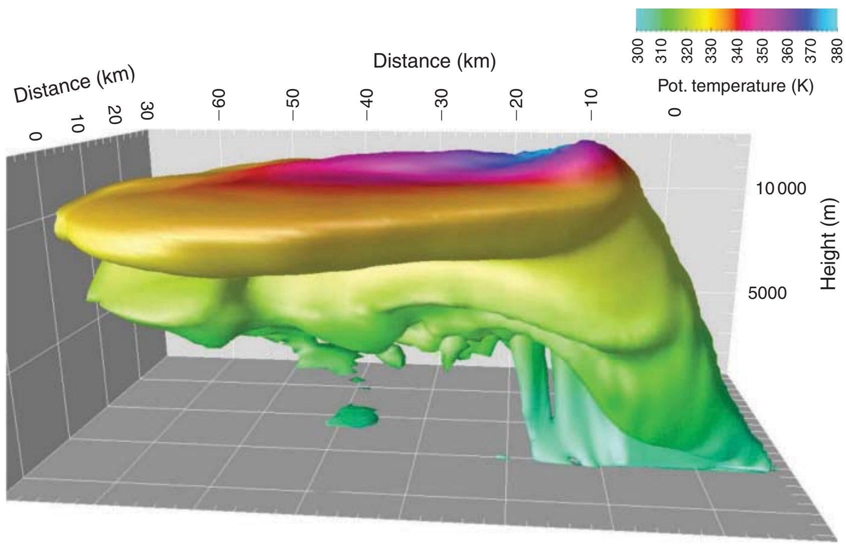

Fig. 4. Simulated 100 μg m^{-3} isosurface of aerosol concentration from ATHAM simulation of Chisholm fire in Alberta Canada, May 2001 (source Luderer *et al.* 2006).

Full physics models

In grid models, the horizontal extent of the grid volumes are usually 4 km^2 or larger, such that the smoke plume at the fire source fits completely within the volume. This prevents the model from resolving any of the relevant dynamic plume processes. Reducing the horizontal extent of the grid volumes from several kilometres down to 50 m or less allows the model to explicitly resolve processes that influence plume development, such as entrainment. This level of resolution removes the need for a plume rise parameterisation as these models incorporate the buoyant flux of pollutants directly into solution of the equations governing atmospheric dynamics. Models operating at this level of detail are based on a form of the Navier–Stokes equations of fluid dynamics (Reynolds averaged Navier–Stokes, large eddy simulation or direct numerical simulation). To more simply describe this class of models, they are referred to as full physics models.

One full physics plume model that has been applied to wildland fire is the active tracer high-resolution atmospheric model (ATHAM) (Oberhuber *et al.* 1998; Herzog *et al.* 1998). Trentmann *et al.* (2002) simulated a prescribed burn in north-western Washington that closely approximated measured elevations and concentrations of smoke. Furthermore, Trentmann *et al.* (2006) and Luderer *et al.* (2006) showed how meteorological dynamics coupled with a large wildfire in Alberta, Canada, to generate a pyrocumulus that reached an altitude of ~13 km. The 100 μg m^{-3} isosurface of aerosol concentration after 40 min of integration is shown in Fig. 4, which gives an example of the detail obtainable with full physics models.

Cunningham *et al.* (2005) used an early version of the height-coordinate form of the Weather Research and Forecasting (WRF) model (Skamarock *et al.* 2001) with a horizontal grid spacing of 10 m to examine vortex dynamics within smoke plumes. Cunningham and Goodrick (2012) used the same model to examine various assumptions used in plume modelling, such as the Gaussian distribution and Briggs (1975) plume rise equations. For simulated heat release rates consistent with understory prescribed fires in the south-eastern United States, the Briggs plume rise equations agreed well with the more detailed simulations. However, the horizontal distribution of smoke was found rarely to be Gaussian, but rather bimodal as counter-rotating vortices tended to enhance plume entrainment along the plume centerline. Cunningham and Reeder (2009) also successfully applied the model to simulations of intense wildfires and resulting pyro-cumulus.

An interesting derivation from the full physics model is the ALOFT plume model from the United States National Institute of Standards and Technology (NIST) which is descended from the work of McGrattan *et al.* (1996). ALOFT (A Large Outdoor Fire plume Trajectory model) predicts the downwind distribution of smoke particulate and combustion products from large outdoor fires by solving the fundamental fluid dynamic equations for the smoke plume and its surroundings. This allows the model to simulate many observed plume features such as the twin counter-rotating vortices frequently observed. The primary simplification that separates ALOFT from the complexities of a full physics model is that ALOFT solves the steady-state form of the convective transport equations using constant ambient atmospheric conditions.

Smoke modelling frameworks

Although the dispersion models discussed represent a broad range of approaches to simulating the transport and dispersion of smoke from a wildland fire, they only represent a fraction of the complexity of the smoke modelling problem. Tools for describing fuel loading, calculating fuel consumption and converting that consumption to emissions, as well as tools for estimating plume rise, are all required to fully treat the smoke management problem. The vast array of expertise required in using these tools can be daunting to land managers. Reducing

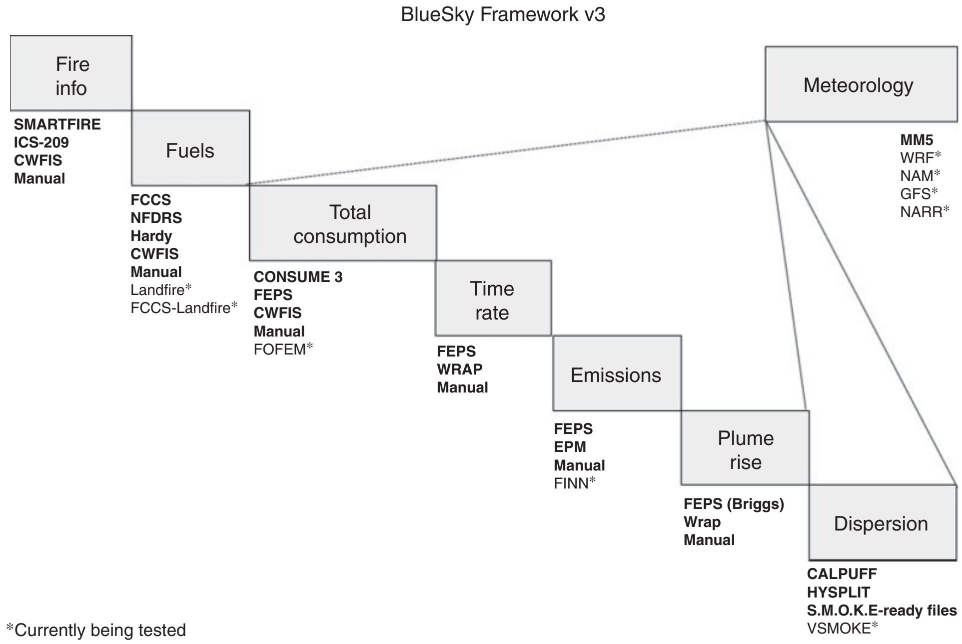

Fig. 5. The current BlueSky Smoke Modelling Framework including both standard distribution modules (bold) and those in testing (asterisks). Meteorological model output data are required for the dispersion step, but not for the consumption step. At the consumption step fuel moisture can be adjusted according to local conditions derived from satellite information (Tropical Rainfall Measuring Mission data) or a local weather station.

this learning curve is the job of smoke management frameworks, a term that describes a modelling structure that combines a set of tools for each component of the smoke modelling process (fuel load, consumption, emissions, plume rise and transport and dispersion) into a unified tool chain that hides much of the underlying complexity from the end users.

The BlueSky Smoke Modelling Framework (BlueSky) was developed as part of a multi-agency effort to simulate and predict smoke from approved or planned prescribed fires, agricultural fires and wildfires (Larkin *et al.* 2009). It couples off-the-shelf weather, fuels, consumption, emissions and dispersion models in a modular framework in order to produce these real-time predictions. By gathering and using information on all fire activity in a region, BlueSky not only predicts the smoke $PM_{2.5}$ effects from a single fire, but also predicts cumulative smoke effects from multiple fires. BlueSky supports a wide array of potential configurations as there is a range of options for each link in the tool chain (Fig. 5). For example, options for dispersion modelling include CALPUFF and HYSPLIT, and CMAQ-ready emissions output can also be generated. Validation efforts for BlueSky have found the predicted plume footprints to agree well with satellite observations; the older version of the framework showed a tendency to underestimate near-field surface smoke concentrations while potentially overestimating far-field surface smoke concentrations (Riebau *et al.* 2006). However, a comparison study between BlueSky–CMAQ output and observations for the 2008 northern California wildfires showed BlueSky version 3.0 predicting $PM_{2.5}$ concentrations near observed values the majority of the time (Strand *et al.*, in press). In addition, the under-prediction bias is no longer evident. These improvements are a result of subsequent sensitivity studies that found that surface smoke concentrations could be improved by modifying how a fire was represented in the framework. Splitting fires into multiple emissions sources to mimic the concept of multiple-core updraft plumes offered improvements to the surface smoke predictions without altering the agreement with satellite detected plumes.

Several smoke modelling systems have been developed from BlueSky including regional systems in the Pacific Northwest and elsewhere (O'Neill *et al.* 2009), web-based custom modelling tools and more fully integrated atmospheric chemistry modelling systems such as the Southern Smoke Simulation System (4S). This system (Liu *et al.* 2010) couples the contribution of smoke from wildland burning with the overall air pollution budget over the south-eastern United States, employing CMAQ for transport and dispersion and atmospheric chemistry. A unique aspect of 4S is the integration of DaySmoke with CMAQ to handle the vertical distribution of pollutants from wildland fires, allowing multiple-core updraft plumes to be simulated.

Future

A key area of uncertainty mentioned in many of the modelling studies cited in this review involves the dynamics of the buoyant phase of the smoke plume that determines its final rise height and the vertical distribution of pollutants. The models presented here cover the spectrum of potential ways of dealing with plume rise: instantaneous, homogeneous mixing, prescribed fractions of emissions released at surface and top of mixed layer, parameterisations such as Briggs (1975), or the explicit numerical simulation based on fundamental atmospheric dynamics. In general, the basic dynamical processes that govern plume behaviour such as entrainment are well understood, but the fire information provided as initial conditions to the smoke management tool chain (total area burned and fuel loading) provide no information on the fire behaviour that would allow for anything more than a generalised plume description for all wildland fires. Although the concept of multiple-core updraft plumes has been useful in improving several dispersion simulations, there is currently no method for estimating the number of cores for a given fire. Plume photographs have provided some guidance on the number of updraft cores, but these supply singular snapshots of the time-varying plume structure. Full physics models provide an excellent means for examining plume behaviour across a wide range of conditions and may be able to provide insight into plume structures which could be quite useful in examining various ignition techniques for prescribed fires.

Early transport and dispersion modelling studies focussed on industrial point sources that were relatively easy to describe. Other source types such as line and area sources grew from this early point source description. Wildland fires represent complex sources that vary in both space and time. To truly describe wildland fires as an emissions source will require linking with fire behaviour models to capture the space–time variability of heat and pollutant release rates across the landscape. Valente *et al.* (2007) describe the first attempt at such a system; linking the FireStation fire spread model and the DISPERFIRE Lagrangian particle model. This system allows the plume rise to be determined for each cell based on the heat release rate within the cell using the plume rise relationships derived by Sestak and Riebau (1988). Results show that the coupled approach provides good agreement with observations and is therefore an avenue for future work to improve the smoke management process.

Moving to a more complete description of wildland fires as a pollutant source requires more than just improved coupling between the fire and atmosphere. Forest vegetation can have significant effects on boundary- and surface-layer structure by altering the distribution of turbulent kinetic energy and turbulent heat and momentum fluxes that, in turn, affect the local and within-canopy transport and diffusion of smoke from wildland fires, particularly low-intensity surface fires (K. L. Clark, N. Skowronski, M. Gallahger, W. E. Heilman, J. L. Hom, M. Patterson, X. Bian and R. P. Shadbolt, unpubl. data, 2011). The development and implementation of fully resolved canopy sub-models within atmospheric models to improve dispersion predictions for low intensity fires as proposed by M. Kiefer, S. Zhong, W. Heilman, J. Charney, X. Bian and R. Shadbolt (unpubl. data, 2011) may improve our ability to predict local smoke effects.

The array of tools that comprise the smoke management tool chain, coupled with a lack of quantitative information on the limitations of each component, presents land managers with a difficult task in determining what tools to use in a given situation. The Smoke and Emissions Model Intercomparison Project (SEMIP), funded by the Joint Fire Sciences Program, addresses both the need for rigorous, quantitative assessment of all available smoke and emissions models and the need to translate such information into usable guidance for use by decision-makers and regulators. Rather than focussing on comparison of a single model type such as fuel consumption model, SEMIP compares all models in the smoke management tool chain. In addition, through SEMIP smoke modelling datasets will be available for model testing, analysing and development.

Conclusion

This review focuses on smoke modelling tools that are used operationally or present significant advances in smoke modelling, and is in no way an exhaustive review of air quality models. Significant knowledge gaps remain, particularly in areas of plume structure such as those related to multiple-core updraft plumes. The fundamental science governing atmospheric transport and dispersion is fairly well-established, particularly for non-buoyant emissions. Currently, the evolution of strongly buoyant plumes such as a smoke plume is poorly described in most models. The time varying spatial distribution of heat release across the landscape, and its effect on plume development, is largely neglected in most modelling efforts due to the complexity of quantifying this type of source. The variance in surface heat due to the fire is an acknowledged integral component of modelling smoke dispersion and transport, as the heat links the fire-source to the atmosphere. The next big advance in smoke modelling will involve moving beyond the current methodologies for determining plume rise to a more complete description of plume structure capable of embodying a range of plume behaviours characteristic of wildfires and the myriad plume structures that can be engineered by prescribed fire ignition patterns.

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