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A comparison of three approaches for simulating fine-scale surface winds in support of wildland fire management. Part II. An exploratory study of the effect of simulated winds on fire growth simulations

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Abstract. The effect of fine-resolution wind simulations on fire growth simulations is explored. The wind models are (1) a wind field consisting of constant speed and direction applied everywhere over the area of interest; (2) a tool based on the solution of the conservation of mass only (termed mass-conserving model) and (3) a tool based on a solution of conservation of mass and momentum (termed momentum-conserving model). Fire simulations use the FARSITE fire simulation system to simulate fire growth for one hypothetical fire and two actual wildfires. The momentum-conserving model produced fire perimeters that most closely matched the observed fire spread, followed by the mass-conserving model and then the uniform winds. The results suggest that momentum-conserving and mass-conserving models can reduce the sensitivity of fire growth simulations to input wind direction, which is advantageous to fire growth modellers. The mass-conserving and momentum-conserving wind models may be useful for operational use as decision support tools in wildland fire management, prescribed fire planning, smoke dispersion modelling, and firefighter and public safety.

Additional keywords: fire behaviour modelling, wildland fire decision support, wind modelling.

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Introduction

Wildland managers considering fire-related treatments and effects are often faced with competing management options complicated by complex interactions between fire and the environment. Fire behaviour predictive tools are often used to support the management decision process (Andrews and Bevins 2003; Stratton 2004). Thus, improvements in wildland fire predictive capability can have positive effects on land management decision effectiveness, including fire suppression and control.

Prediction of wildland fire behaviour requires accurate knowledge of vegetation, weather, and topography (Albini 1983; Rothermel 1983). A fire burning under the influence of wind can change dramatically in intensity and spread direction with associated changes in wind. Near surface wind in mountainous topography often fluctuates on small temporal and spatial scales (Fang and Steward 1969; Pyne *et al.* 1996; Wakes *et al.* 2010). Error in fire prediction can come from a range of sources including fuel and terrain descriptors as well as inadequate descriptions of local winds, and of course the fire models themselves.

The most widely used wildland fire growth and intensity models in the US (in an operational sense) are based on parameterisations of heat transfer, fluid flow and chemical reactions developed from experimental work (Rothermel 1972; Van Wagner 1977). The main advantages of these models are that they are simple to run and have fast solution times (Andrews 1986; Finney 1998). Other more physically sophisticated models have been developed (Clark *et al.* 1996; Grishin 1997; Linn 1997; Porterie *et al.* 2000; Mell *et al.* 2007). These models include coupling effects of fire-generated buoyancy on the surrounding fluid flow as well as detailed treatment of heat transfer. Although in theory these models should be more accurate than simpler models, they come with higher computational costs, often complex data requirements, and in some cases require sophisticated user knowledge. For these and other reasons, they are not currently used operationally for fire management.

A possible solution to bridge the gap between the simple and more complex fire growth models is to simulate the wind near the ground surface without coupling the flow to the fire and then use that wind field in the simple fire growth models. Such an approach would move a step closer to the more physically based models, while allowing the use of the current semi-empirical fire spread models and still meeting the operational time, computing and knowledge constraints (Butler *et al.* 2006).

A similar approach was followed by Lopes *et al.* (2002), who combined two diagnostic wind models that are similar to those used in this study with a cellular-based fire growth model. The wind models were a mass-conserving model and a mass–momentum-conserving model. Since its development the combined wind–fire growth model has not seen widespread use operationally; the reasons for this are unclear but likely related to the lack of integration in the fire simulation systems developed in the US and the fact that the source code is proprietary. Others have explored the use of computational fluid dynamics models like those explored in this study for simulating near earth boundary layer flow associated with large urban fires (Shiraishi *et al.* 1999) as well as flow over mountainous terrain (Apsley and Castro 1997; Wood 2000). Despite this earlier work, questions remain about the effect of high-resolution wind information on fire simulations from operational fire models used in the US.

The first paper of this two-part series describes two diagnostic wind models and compares simulated and measured wind fields for two geographical locations (Forthofer *et al.* 2014). Although diagnostic wind models have been investigated for use in other fields, such as wind power generation and pollutant dispersion, there are comparatively few studies documenting their use in support of wildland fire management (Forthofer 2007; Forthofer *et al.* 2014).

The primary objective of this study is to explore the effect of wind fields generated from two wind models and from a uniform wind field (traditional approach) on fire growth simulation accuracy. The wind models are (1) a uniform wind field that represents the typical data received from large-scale weather service forecast models; (2) a model that accounts for conservation of mass only, hereafter *mass conserving*; and (3) a diagnostic model that accounts for conservation of mass and momentum, hereafter *momentum conserving*. Fire perimeters generated using the three wind models as input are compared to observed fire locations for one hypothetical and two actual fires. The wind and fire are simulated in a decoupled fashion: that is, the winds are computed and then input into the fire model – there is no feedback from the fire model on the modelled wind field. This is a generally accepted approach given the computing limitations associated with wildland fire decision support. The wind models are not prognostic: they do not forecast winds forward in time, but rather predict the spatially varying time-averaged winds that will occur at a particular point in time over the specified terrain. The predicted winds do not account for any temporal variation in the flow field. As a result, we do not explore the growth of the fire over an extended period but rather focus on the growth associated with one primary wind event during which we assume that the wind speed and direction is nominally steady. Future efforts will explore fire growth over longer time frames associated with time-varying winds, such as diurnal flows.

Methods

Fire growth model

The FARSITE fire modelling system (Finney 1998) was used for the fire growth simulations in this study. FARSITE incorporates models of surface fire growth, crown fire spread rate, point-source fire acceleration, spotting and fuel moisture. Fire spread in two dimensions was accomplished using a one-dimensional spread rate model and the assumption of an elliptical two-dimensional fire shape. Users have two options for wind input. The standard selection is to use uniform, non-spatially varying winds in the form of a FARSITE .WND file. This file must contain wind speed and wind direction at 6.1 m above the vegetation, and cloud cover for discrete times spanning the simulation duration. These values are applied across the entire landscape. The other option is to use a spatially varying wind field. In FARSITE, this is called a 'gridded wind'. An .ATM file is constructed that includes wind speed, wind direction and cloud cover file names for discrete time segments and spatial locations that span the simulation duration. Additional information on using gridded winds can be found in Finney (1998) and Stratton (2006).

Wind models

As discussed in Stull (1988), wind flow can be characterised as consisting of a mean, and deviations or perturbations from that mean. The wind models evaluated here were developed from a reduced set of relevant physical processes, essentially based on the assumption that from a practical standpoint the major aspects of wind speed and direction can be determined from either solution of only conservation of mass, or alternately solution of conservation of mass and momentum (i.e. accounting for turbulence). The wind models assessed here are intended to simulate mean wind flows such as those associated with a frontal passage, where the mean flow is generally significantly greater than the fluctuations about the mean. Wind flows generated by solar heating or cooling, such as up- or down-slope flows, are not accounted for. The models should be applicable for intense up- or down-canyon flows, such as Santa Ana or Sundowner winds, but verification of this is left for future study.

Uniform wind field

Traditionally, operational fire models have used a single domain-average wind throughout the modelling domain. The primary reason is because wind data obtained from operational synoptic scale forecasts provides wind predictions at the scale of 5–15 km, and thus for most fires only one or at most a few wind data points are available. In this study a spatially uniform wind field was used in one set of fire growth simulations. The wind speed and direction were selected based on the nearest weather station and local observations.

Mass-conserving wind model

The second set of fire growth simulations were based on a wind field generated from the mass-conserving model. This model mathematically minimises the change from an initial wind field with an imposed boundary condition while strictly conserving mass. A more detailed description of the modelling approach is provided in Part I (Forthofer *et al.* 2014). Typical wind simulations take ~1–2 min to reach convergence on a single-processor computer for a domain nominally 25 × 25 km and 5 km high consisting of ~1 million cells.

In all simulations the modelling domain was initialised using one wind speed and direction at a specified height above the ground. The domain is filled vertically assuming a neutrally stable logarithmic wind profile and a roughness height for the dominant vegetation in the area (Wieringa 1993).

Momentum-conserving wind model

The last set of fire growth simulations was based on a momentum-conserving wind model. This model conserves both mass and momentum, includes a turbulence sub-model and depends on the commercial solver Fluent (see www.fluent.com, accessed 1 February 2006). A detailed description of the momentum-conserving model can be found in Forthofer *et al.* (2014). The fire area was placed far enough downstream so that a boundary layer would develop before reaching the fire location. Appropriate roughness parameters for vegetation were obtained from Wieringa (1993). Typical computational domains nominally 25×25 km and 5 km high consisted of $\sim 1 \times 10^6$ cells. Wind simulations took ~0.5–1.5 h on a single-processor computer. Both models produce wind speed and direction at user specified height, which for this study was 6.1 m above ground level (AGL).

Simulated fires

Fire simulations were conducted for three locations: (1) Askervein Hill, (2) the South Canyon fire and (3) the Mann Gulch fire. The Askervein Hill simulation is a hypothetical fire on a low elevation, simple-geometry hill. This simulation was chosen to investigate the effect of the wind-modelling approach on fire spread for a distinct wind event and terrain feature for which the wind model accuracies are known (Forthofer *et al.* 2014). This simulation does not include a comparison against an actual fire event, but explores the relative influence of the three wind-modelling approaches on fire growth that could be expected for the terrain feature, winds and vegetation. The South Canyon and Mann Gulch fires were selected for three reasons: (1) because published investigations (Rothermel 1993; Butler *et al.* 1998) exist that include relevant weather and fire behaviour information; (2) the fires included a period of high fire growth linked to a single wind event; and (3) fire behaviour was complex and not readily explained using existing fire modelling capabilities. Many other fires could have been simulated but the authors believe these three examples demonstrate the effect of wind-modelling systems over a range of vegetation and terrain conditions. Future studies will explore performance of the models for fires in different locations.

Askervein Hill

Askervein Hill (57°11.313′N, 7°22.360′W) was the site of a large wind measurement study (Taylor and Teunissen 1983, 1985). Comparisons between measured and simulated winds show that both wind models accurately simulate the wind speed on the upwind side of the hill and at the top. However, the momentum-conserving model did a better job predicting the speed on the lee side of the hill. Both models had difficulty predicting wind direction on the lee side of the hill (Forthofer *et al.* 2014).

A hypothetical fire was simulated on Askervein Hill to illustrate the differences in fire spread that can occur with the two types of wind models and a uniform wind field for a topographically simple hill for which detailed wind measurements exist. The fuel and weather conditions (other than wind speed and direction) used in all fire simulations are shown in Table 1. The hypothetical fire was ignited upwind of Askervein Hill as a point ignition and allowed to spread for 3 h. For the uniform wind simulation, a wind velocity of 8.9 m s^{-1} at 10 m AGL was used. This same wind velocity was also used to initialise the momentum-conserving and mass-conserving wind fields. All computational grids had a 40-m horizontal resolution.

Table 1. FARSITE inputs for the Askervein Hill simulations

Variable	Setting
Fuel model	2
Canopy cover	0%
Temperature	26.7°C
Relative humidity	20%
1-h fuel moisture	5%
10-h fuel moisture	6%
100-h fuel moisture	7%
Live herbaceous fuel moisture	100%
Live woody fuel moisture	100%
Fire spread rate adjustments	1
Time step	10 min
Perimeter resolution	25 m
Distance resolution	25 m
Only surface fire, no spotting	

Table 2. South Canyon Fuel Model (FM) cross-walk from digital orthophoto quadrangle (DOQ) values to standard FMs used in BEHAVE and FARSITE (Anderson 1982)

DOQ value	FM
71–150	4 (chaparral or other flammable shrubs)
151–190	2 (forest grass and understorey vegetation)
191–300	99 (barren, rock)

South Canyon fire

Complex mountain winds were cited as one of the most important variables influencing the fire behaviour on 6 July 1994 when the South Canyon fire overran and killed 14 firefighters (Butler *et al.* 1998). Digital orthophoto quadrangles and descriptions of the fuels (Butler *et al.* 1998; Miller and Yool 2002; Stratton 2004; Finney *et al.* 2007) were used to develop a spatially explicit fuels map for the simulation based on the standard fuel models presented by (Anderson 1982) (Table 2). Similar techniques have been used successfully by others to generate spatial fuels information (Miller and Yool 2002; Stratton 2004; Finney *et al.* 2007). Vegetation consisted of Fuel Model (FM) 2 (forest with grass and understorey vegetation) and FM 4 (chaparral or other flammable shrubs) (Anderson 1982) (Fig. 1). Canopy cover was 0% across the landscape. Weather data from the Rifle, Colorado remote automated weather station (RAWS), located ~16 km west of the fire location, were used for temperature and relative humidity during the simulations. Air temperature was 29°C and relative humidity was 8%. The RAWS recorded sustained winds of up to 13.4 m s^{-1} from the

Fig. 1. Fuel Model (FM) map at 10-m (33-feet) resolution for the South Canyon fire vicinity. FM 4 – green; FM 2 – tan; FM 99 (barren, rock) – grey. The white dotted line indicates the fire perimeter before the blowup, the red dotted line is the West flank fireline and the purple dotted line indicates the main ridge fireline. Helispots 1 and 2 are indicated by H1 and H2. The 'Zero Point' is where the west flank fireline meets the ridgetop (Butler *et al.* 1998). The contour lines (12-m interval) and shading show the terrain relief.

west-south-west with gusts up to 20 m s^{-1}. Butler *et al.* (1998) estimated peak ridge top winds in the fire area of over 22 m s^{-1}. Model settings used in FARSITE for the South Canyon fire simulations are listed in Tables 2–5. Fire model spread rate adjustment factor and percentage ignition frequency were varied to achieve the best fit between observed and simulated fire perimeters (Table 4).

The computational domain was constructed from a 30-m resolution digital elevation model (DEM) that was 7.4 × 5.7 km in extent. Four general wind directions – 180, 225, 250 and 270° – were simulated to bracket the wind direction that occurred based on RAWS data. The input speed values for each simulation were adjusted to produce 6.1-m ridge top wind speeds near Helispots H1 and H2 of 22–25 m s^{-1} as determined from witness statements obtained after the fire event. For the uniform wind fields, wind speed was 14.8 m s^{-1}. This value was chosen because it represents the average of the high winds reported at the ridges and the lower wind speeds in the drainages, and in preliminary fire spread simulations produced fire progressions that best matched the observed.

Mann Gulch fire

The Mann Gulch fire overran 16 firefighters, killing 13 in the Helena National Forest in Montana on 5 August 1949 (Rothermel 1972; Maclean 1992; Rothermel 1993). The fire burned in steep terrain during a cold front passage that was characterised by 18-m s^{-1} wind speeds primarily from the south. Based on Rothermel (1993), critical locations and times for the fire progression are shown (Fig. 2). Smokejumpers landed in Mann Gulch at 1600 hours MDT (Mountain Daylight Time). While hiking down the drainage at ~1740 hours they noticed that spot fires they had seen earlier had coalesced and were burning upslope out of the gulch below them. The crew reversed

Table 3. FARSITE settings for the South Canyon fire simulations

Variable	Setting
Canopy cover	5%
Stand height	3 m
Crown base height	0.1 m
Crown bulk density	0.15 kg m^{-3}
Canopy foliar moisture content	100%
Canopy tree diameter	10 cm
Shade tolerance of torching trees	Medium
Torching species	Douglas-fir
Initial 1-h fuel moisture	3%
Initial 10-h fuel moisture	4%
Initial 100-h fuel moisture	5%
Initial live herbaceous fuel moisture	60%
Initial live woody fuel moisture	60%
Model time step	1 min
Perimeter resolution	20 m
Distance resolution	15 m
Crown fire	Enabled
Crown density and cover	Linked
Embers from torching trees	Enabled
Spot fire growth	Enabled
Fire level distance checking	On
Fire acceleration	On
Duration: preconditioning start	2-Jul-1994
Duration: simulation start	6-Jul-1994, 1607 hours
Duration: simulation end	6-Jul-1994, 1623 hours

Table 4. Rate of spread adjustment and spot fire ignition frequencies used in the South Canyon fire simulations

Wind model	Direction (°)	Rate of spread adjustment	Spot fire ignition frequency (%)
Uniform	180	1.0	0.8
Mass conserving	180	1.0	0.9
Momentum conserving	180	1.5	2.0
Uniform	225	1.0	0.8
Mass conserving	225	1.0	0.9
Momentum conserving	225	3.0	3.0
Uniform	240	1.0	1.0
Mass conserving	240	2.0	1.0
Momentum conserving	240	1.5	1.0
Uniform	250	1.0	1.0
Mass conserving	250	2.0	2.0
Momentum conserving	250	2.0	1.0
Uniform	260	1.0	0.8
Mass conserving	260	2.0	1.0
Momentum conserving	260	2.0	1.0
Uniform	270	1.0	0.8
Mass conserving	270	2.0	1.0
Momentum conserving	270	3.0	3.0

Table 5. FARSITE settings for the Mann Gulch Fire simulations

Variable	Setting
Rate of spread adjustment	1.8
Initial 1-h fuel moisture	5%
Initial 10-h fuel moisture	8%
Initial 100-h fuel moisture	12%
Initial live herbacious fuel moisture	100%
Initial live woody fuel moisture	100%
Model time step	3 min
Perimeter resolution	15 m
Distance resolution	15 m
Crown fire	Disabled
Embers from torching trees	Disabled
Spot fire growth	Disabled
Fire level distance checking	On
Fire acceleration	On
Duration: preconditioning start	8/2/1949
Duration: simulation start	8/5/1949, 1720 hours
Duration: simulation end	8/5/1949, 1800 hours

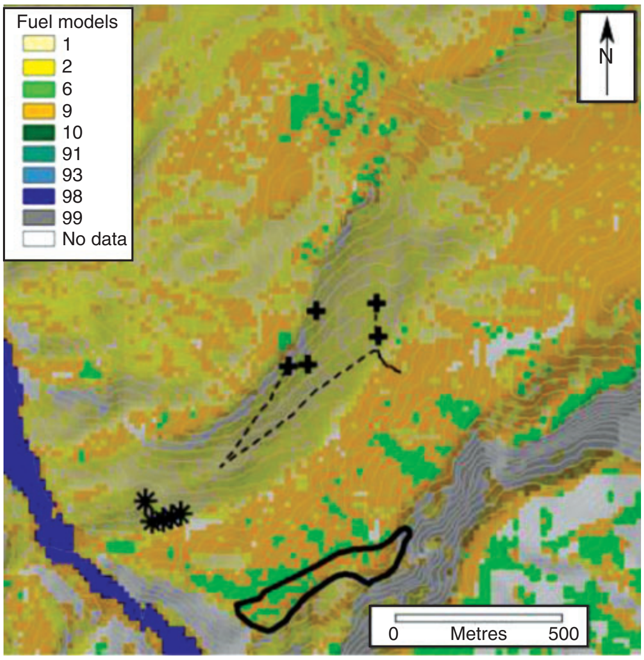

Fig. 2. Fuel map used in simulations of the Mann Gulch fire area. Contour line spacing is 30-m vertical. North is towards the top of the image. Locations identified are from Rothermel (1993). The asterisks represent spot fire locations at ~1730 hours. The crosses represent the locations of firefighters at time of burnover, the dashed lines represent path taken by crew and the solid black line represents the known fire perimeter at 1600 hours (approximately the time that firefighters arrived on the fire).

their direction and began hiking uphill towards the ridge. The fire overtook the crew between 1755 and 1800 hours.

Visual interpretation of pre-fire aerial photos and descriptions were used to adjust the LANDFIRE FBFM13 data (Rollins and Frame 2006) to reflect the fuel conditions that existed before the fire as described in Rothermel (1993). FM 5 (shrubs and brush) was changed to FM 2 (grass and understorey litter in forests), and FM 8 (short conifer needle litter) was changed to FM 9 (long needle conifer litter) (Anderson 1982) to better correspond to descriptions of the fuels in 1949. On slopes with aspects between 270 and 328°, FM 2 (grass and understorey litter in forests) was changed to FM 9 (long needle conifer litter) to correspond to the aerial photos.

No documented perimeters of the fire are available but witness statements indicated where spot fires were located when the smokejumpers arrived. The fire spread from the spot fire located near the mouth of the drainage to where the firefighters were killed in ~30 min (Rothermel 1993), thus a starting point and ending point with spread time are known. The motivation for simulating fire growth on this fire stems from persistent questions about how the fire moved in the direction and speed that was observed, and the failure of current operational fire models to successfully simulate such fire growth, while recognising that the growth that caused the fatalities was associated with a frontal passage. The performance of the simulations was judged by how accurately the fire model simulated the arrival of the fire at the fatality locations at the appropriate time when initiated at the observed spot fire locations. To do so the fire model had to have accurately simulated the cross-slope fire run up the gulch over the times spanned by the major action points identified by Rothermel (1993).

The modelling domain used for wind simulations was 22×26 km. Five different wind directions were used – 135, 180, 190, 225 and 270° – bracketing the 180° wind speed measured at the airport in Helena, MT (~32 km south-south-west of the fire) and the 225° direction at Mann Gulch estimated by (Rothermel 1993). Simulations of both the momentum-conserving wind model and the mass-conserving model were run with input speeds that gave ~18-m s^{-1} winds at the 6.1-m height at the ridge top where the firefighters died. A uniform 6.1-m wind speed of 8 m s^{-1} was used, which is an estimated average of the true wind field in the area based on observations.

Model evaluation methods

The fire growth evaluations were conducted using two approaches. The first approach held fire model adjustment parameters constant for all wind directions. The second approach varied the fire model parameters to obtain the best match between simulated and observed fire perimeters. The first approach was used for the Askervien Hill and Mann Gulch fire simulations, where actual fire perimeter data were not available. The second approach was used for the South Canyon simulations, where available fire perimeter data were available to evaluate simulated perimeters based on various model setups. This approach isolated the effect of the wind model from that of the fire model variables and allowed evaluation of the wind effect assuming all other fire model parameters were adjusted to their 'best' values.

For the South Canyon fire simulations, the spread rate adjustment parameter and ignition frequency were adjusted to obtain the best fit as determined from visual assessment of predicted and actual fire perimeter location. 'Rate of spread adjustment' is a multiplier of the computed spread rate and 'percentage ignition frequency' controls how many of the lofted embers that land in burnable fuels actually start a spot fire. A rate of spread adjustment factor is often used by fire analysts to quickly adjust the spread rates of a fire simulation for calibration of the model to observed fire behaviour (Churchill Sanders 2001; Stratton 2006). Stratton (2006) recommends starting simulations at values ~0.5–1.0% spotting ignition frequency. The settings used in FARSITE are shown in Table 5.

For the Askervien Hill fire the simulated and expected fire perimeters were assessed based on expectation of fire growth given the terrain, vegetation and winds. The three wind models result in three distinct fire growth patterns. We assessed these patterns based on logical fire response to wind and slope.

Published information about the Mann Gulch fire includes the location of fires burning near the mouth of the canyon at the time that firefighters arrived on the fire and the location and time of firefighter fatalities a short time later. For this analysis the fire simulation was started when fires were observed near the canyon mouth. Although no published perimeters exist, the analysis focussed on the capability of the different wind–fire growth modelling approaches to accurately capture the fire arrival at the fatality sites over the observed time frame.

For the South Canyon fire, two different methods of comparing the simulated fire perimeters with the observed perimeters were used. The first was to visually compare the perimeters. Others have stated that this method of comparison is most often used and can give insight into modelling accuracy (Sanderlin and Van Gelder 1977; Anderson *et al.* 1982; Xu and Lathrop 1993; Finney 1994; Finney 1995; Coleman and Sullivan 1996; Finney 2000). The second method of comparison was to compute the simulated areas that overlap, under-predict and over-predict the observed fire perimeter at a specific time during the fire's progression (Churchill Sanders 2001). Three areas are reported here as percentage of total observed area to allow easier interpretation.

Others have indicated that it is not possible to fully 'validate' the models (i.e. for the purposes of this study, combinations of fire and wind models) because the error of the input data and observed data used for comparison are not controlled or known (Rykiel 1996). Indeed, Albini *et al.* (1982) and Finney (2000) concluded that full validation of FARSITE and the Rothermel (1972) spread equations is not possible. However, useful information about model performance can be gained from observation of model response to perturbations in input parameters. For this reason the comparisons made in this study are presented as primarily illustrative and exploratory given the uncertainty in fire perimeters, wind inputs, and fuel parameters.

Results

Askervein Hill

In the uniform wind case, the effect of the hill was almost unnoticeable (Fig. 3). The fire pattern closely resembled an ellipse, suggesting that fire spread rate was dominated by the wind with little terrain influence. The fire spread pattern for the mass-conserving wind field simulation was slightly different, but still resembled an ellipse with little influence of terrain slope. The fire spread pattern for the momentum-conserving wind field from ignition to the top of the hill was consistent with the mass-conserving simulation. However, downwind of the hill, the fire entered an area of significantly lower wind speed and opposing slope and direction which led to a significantly lower fire spread rate on the lee side of the hill and a dramatic change in the fire shape compared to the other simulations (Fig. 3).

South Canyon

Fig. 1 shows the steep, dissected terrain and the main drainage of the Colorado River in the area of the South Canyon fire. Simulated winds for the 270° direction are shown in Fig. 4. It is apparent that the momentum-conserving model produced a wind field with more turning or channelling of the wind from terrain-induced effects than the mass-conserving model. In general, both models show higher wind speeds near the ridge tops and lower wind speeds near the drainage bottoms.

The simulated fire spread for simulations associated with input wind directions of 180, 225, 250 and 270° are shown in Fig. 5. The FARSITE runs were started from the fire perimeter at 1607 hours. As stated earlier, fire growth model spread adjustment factor and spot fire ignition frequency were adjusted to obtain the best fit for each wind direction. The intent was to compare the influence of the wind model on fire growth when the fire growth model is optimised for the specific fire. The final simulated and observed perimeters shown correspond to a time of 1623 hours. Table 6 shows the results of the percentage area comparisons for input wind directions of 180, 225, 240, 250, 260 and 270° computed using the observed burned area as the normalising area.

For the uniform wind input, it is apparent that the input wind direction had a large influence on the fire progression (Fig. 5). The uniform simulations showed very little fire spread in directions other than downwind, resulting in a simulated fire perimeter approximately elliptical in shape. The sensitivity of the fire spread to the single wind direction is easily seen. Although the overall fire spread distance matched well (which was by design), the shape of the simulated perimeter did not match the observed perimeter well (Table 6). In general, there was not enough lateral (cross-wind or flanking) fire spread. The best uniform simulation, which was a wind from 240°, was coincident with 57% of the observed burned area.

The mass-conserving-based fire growth simulations showed better agreement with the observed perimeter than the uniform wind information (Fig. 5). For most input directions, greater lateral spread of the fire was evident in the images that correlated more closely to the observed perimeter. In all simulations, the mass-conserving runs had higher coincident areas and lower under-prediction and over-prediction areas compared to the uniform wind runs (Table 6).

Momentum-conserving-based fire growth simulations best matched the observed perimeter for most of the directions (Fig. 5). Lateral fire spread was more consistent with the observed fire perimeter. In the percentage area comparisons (Table 6), the momentum-conserving-based runs also had a higher percentage of coincident areas than the mass-conserving and uniform-wind-based runs for all but an input direction of 225°; the highest coincident area was 83.4% for the 270° run. In fact, the 240, 250, 260 and 270° momentum-conserving-based runs all had higher coincident areas than the best mass-conserving-based and uniform wind runs (Table 6). On average, the momentum-conserving-based fire simulations exhibited slightly more over-prediction than the mass-conserving runs but less than the uniform wind runs. If the best and worst

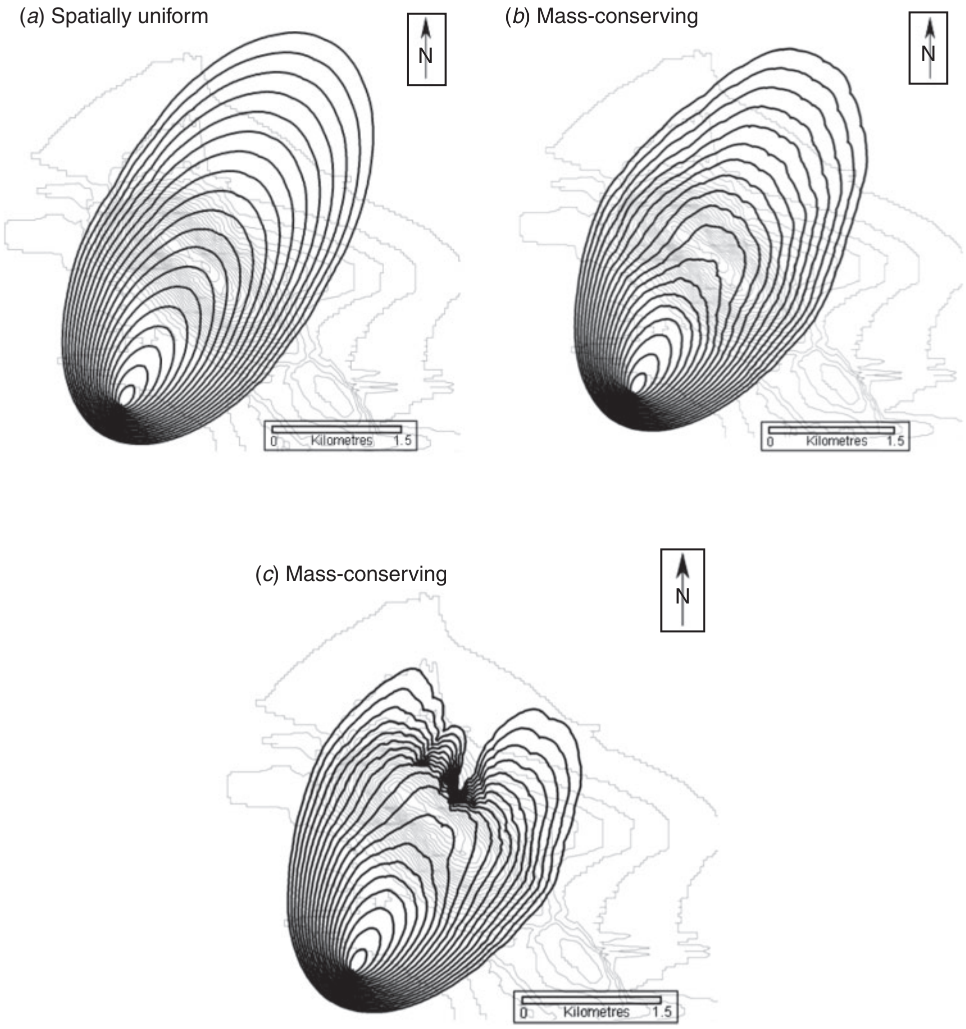

Fig. 3. Comparison of three fire spread simulations for the Askervein Hill area using different wind fields: (*a*) uniform wind, (*b*) mass-conserving wind and (*c*) momentum-conserving wind. Dark lines denote the fire progression spaced 10 min apart, light lines are the 5-m (16.4-feet) elevation contour lines. North is towards the top of the image.

simulations for each type of wind field are disregarded, and the remaining values averaged, the following coincident area averages were: 74.9% for momentum conserving, 55.6% for mass conserving and 46.6% for uniform winds.

Mann Gulch

Fire growth simulations were performed maintaining fire model parameters constant for all wind models and directions. The simulated wind fields for 270° are shown in Fig. 6. The momentum-conserving simulations showed more channelling up Mann Gulch than the mass-conserving simulations. However, the mass-conserving simulations did show some turning of the wind up the drainage. Of course, this turning was not evident in the corresponding uniform wind fields. The momentum-conserving and mass-conserving wind fields also showed low wind speeds near drainage bottoms and higher speeds near the tops of ridges.

The fire simulations were started from the spot fires marked on Fig. 2. The fire growth simulations for the five wind directions and three different wind models are shown in Fig. 7. The line of rock along the ridge formed a barrier to spread in many cases. However, in some simulations the fire spread through gaps in the rock and continued moving to the north.

For the 225 and 270° directions, all of the wind fields produced fire spread that moved up Mann Gulch as mainly a head fire. This matches the observed fire behaviour based on witness statements. For the 135, 180 and 190° directions, none of the uniform wind field simulations resulted in a fire that moved far enough up Mann Gulch to match the reconstructed fire movement. The mass-conserving wind fields spread the fire slightly farther up the gulch in the 180 and 190° directions, more closely matching the observed fire locations. The mass-conserving 135° direction did not push the fire up Mann Gulch. The momentum-conserving wind fields produced fire perimeters that appeared to most closely match reported fire location

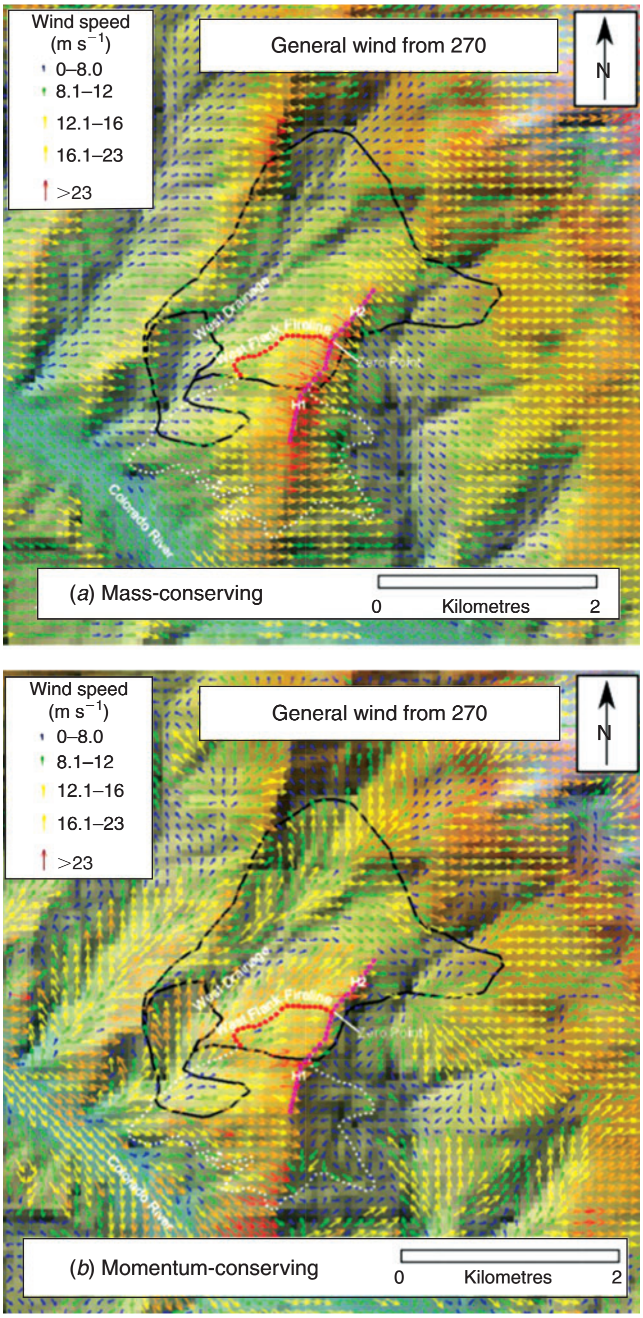

Fig. 4. Wind simulations for the South Canyon fire from the two wind-modelling approaches. The two black outlines are the observed fire perimeters at 1607 hours and 1623 hours on 6 July 1994. The red dashed line is the west flank fireline that is critical to the firefighter entrapment and the white dashed line is the fire perimeter on the afternoon of 6 July 1994 before the arrival of the cold front that led to the explosive increase in fire intensity.

for the 135, 180 and 190° direction cases over the time frame of interest.

Discussion

The low time-averaged winds predicted by the momentum-conserving simulation in the lee of Askervein Hill caused a significant decrease in the spread rate of the fire when compared to the mass-conserving and uniform wind cases. The low wind speeds in this area predicted by the momentum-conserving model more closely matched time-averaged measurements than the other wind-modelling approaches. This observation is supported by current understanding of lee slope flow that would postulate turbulent eddies that would reduce the time-averaged speed (Byron-Scott 1990; Haney 1991; Berg *et al.* 2011). Others have stated that there exists a need for computationally cheap methods for predicting near surface flow (Wood 2000) but that lee slope flow is driven by processes not possible to predict using reduced physics modelling approaches (Eidsvik and Utnes 1997). The fire growth simulations presented here indicate that even under moderate terrain influence, accurate simulation of the mean flow in the lee side of ridges and hills is critical to accurate spread simulations.

For the South Canyon fire, the momentum-conserving-based fire growth simulation was less sensitive to initial wind direction and generally agreed with the observed fire perimeter for all but one input wind direction. The mass-conserving model showed significantly less agreement. Channelling of wind up the West Drainage was a crucial element affecting fire spread (Butler *et al.* 1998). The momentum-conserving and mass-conserving models captured this effect to varying degrees, whereas the uniform wind fields did not. The 225° momentum-conserving based fire growth simulation significantly under-predicted fire progression, even though large values of rate of spread adjustment and spot fire ignition frequency were used (Table 4). The wind field was to blame here, which on inspection, showed low wind speed values in the fire area. These low values occurred because of the location of the upwind domain boundary. The boundary crossed over the top of a large mountain and down to the valleys on the sides of the mountain. The specified boundary condition in the momentum-conserving wind model is one uniform wind speed value along this boundary. Because of this, the wind speed at the top of the mountain is the same as in the valley below it. This is far from reality and is propagated through the domain. The unrealistic wind field on the boundary led to a very large area of low wind speeds downwind from the mountain, which is exactly where the fire simulation took place. This did not occur for other directions because the fire area was outside any low-speed areas, nor was this effect as apparent in the mass-conserving wind simulation. Although not tested in this study it is likely that a larger computational domain would have minimised such boundary effects. Similar results have been reported by others (Kim *et al.* 2000).

For the Mann Gulch fire, the simulations based on the 135, 180, 225 and 270° wind directions using the momentum-conserving wind model gave promising results, whereas only two of the uniform runs and three of the mass-conserving runs showed the potential to match the observed fire spread with some adjustment of fire model parameters. The simulations do point towards the momentum-conserving wind fields producing more accurate fire simulations than the other types of wind fields. The mass-conserving runs appear to give better predictions than uniform winds.

Both Mann Gulch and South Canyon can be considered topographically complex compared to Askervein Hill. The simulations indicate a reduction in sensitivity to input wind

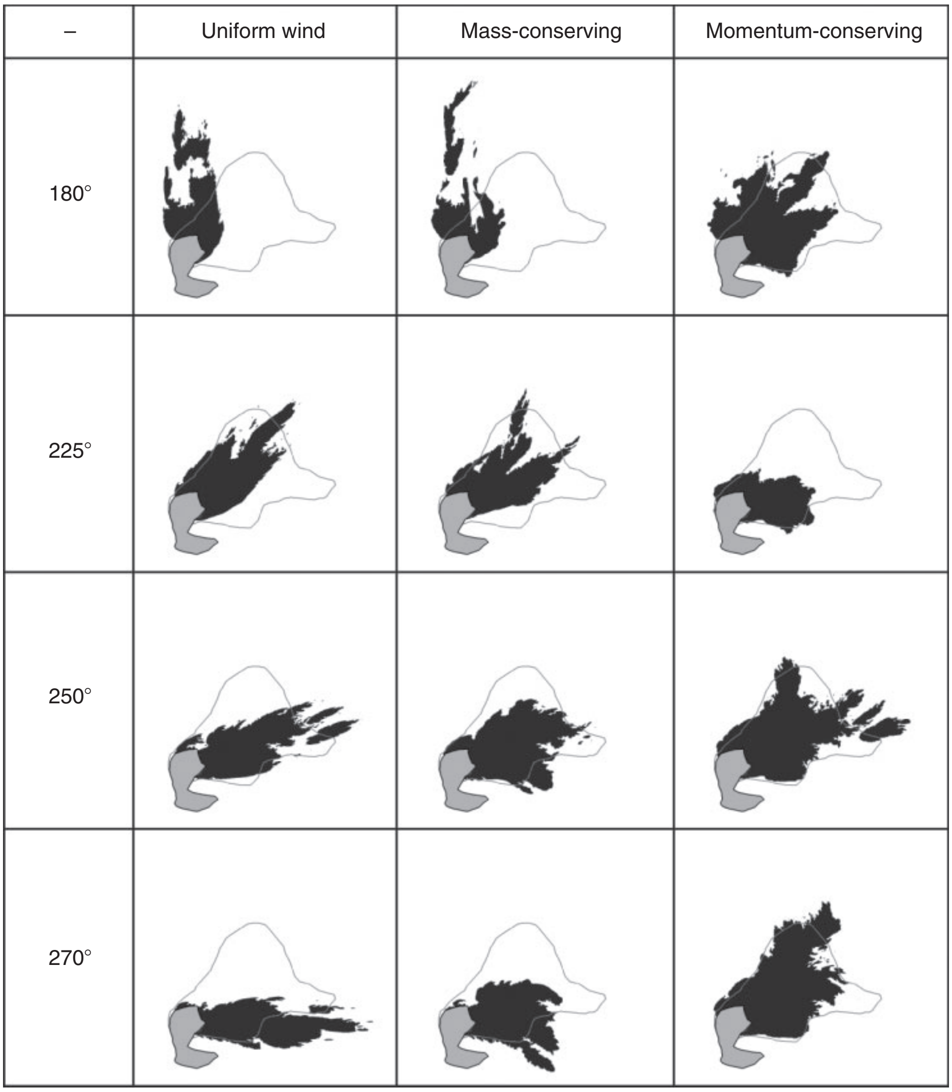

Fig. 5. Comparison of simulated and observed fire perimeters for the South Canyon fire. The grey shaded polygon is the 1607 hours observed perimeter at the beginning of the simulations. The unfilled black lined polygon is the observed 1623 hours perimeter and the filled black polygon is the simulated 1623 hours perimeter. The synoptic wind direction is shown on the left and the wind model used on the top.

direction for topographically complex terrain. Similar effects have been observed for these surface wind models relative to input wind speed; that is, the simulated local wind speed seems to scale linearly with the input wind speed over a $\pm30\%$ range. This suggests that the steering and speed up or down effects generated by interaction between synoptic wind flow and local terrain features dominate the local near surface flow. Therefore, as demonstrated in the South Canyon fire case a user in an operational setting might use the fire spread rate adjustment factor to account for under-prediction or over-prediction of wind speeds.

In general, the momentum-conserving model performed better than the mass-conserving model and the uniform wind field. The obvious explanation for this is that it includes the most extensive physics, for example, conservation of momentum and turbulence. The mass-conserving model outperformed the traditional method of using a uniform wind field. Even though the momentum-conserving model produced better fire spread simulations than the mass-conserving model, both models could be useful to fire managers. The advantage of the mass-conserving model is that simulations take a few minutes, whereas the momentum-conserving model can take up to 1.5 h for a single wind simulation. Often operational constraints of tactical decisions for fire management must be made in very short time frames, which may preclude the use of the momentum-conserving model. Under strict time constraints, the time savings of the mass-conserving model could justify its use.

Only the South Canyon fire simulations constitute a comparison against actual fire perimeters. Thus, any conclusions based on these simulations should be tempered by the need for further

Table 6. Simulated and observed percentage area comparisons for the South Canyon fire simulations

Wind model	Direction (°)	Area coincident (%)	Area under-predicted (%)	Area over-predicted (%)
Uniform	180	14.2	85.8	35.0
Mass conserving	180	18.5	81.5	28.7
Momentum conserving	180	65.7	34.3	23.8
Uniform	225	51.8	48.2	8.6
Mass conserving	225	56.5	43.5	6.6
Momentum conserving	225	37.1	62.9	4.6
Uniform	240	57.1	42.9	11.0
Mass conserving	240	73.3	26.7	10.1
Momentum conserving	240	80.6	19.4	11.2
Uniform	250	55.3	44.7	14.1
Mass conserving	250	65.7	34.3	9.8
Momentum conserving	250	78.3	21.7	26.4
Uniform	260	48.1	51.9	24.6
Mass conserving	260	54.1	45.9	12.9
Momentum conserving	260	74.8	25.2	13.8
Uniform	270	31.3	68.7	30.5
Mass conserving	270	45.9	54.1	16.4
Momentum conserving	270	83.4	16.6	19.7

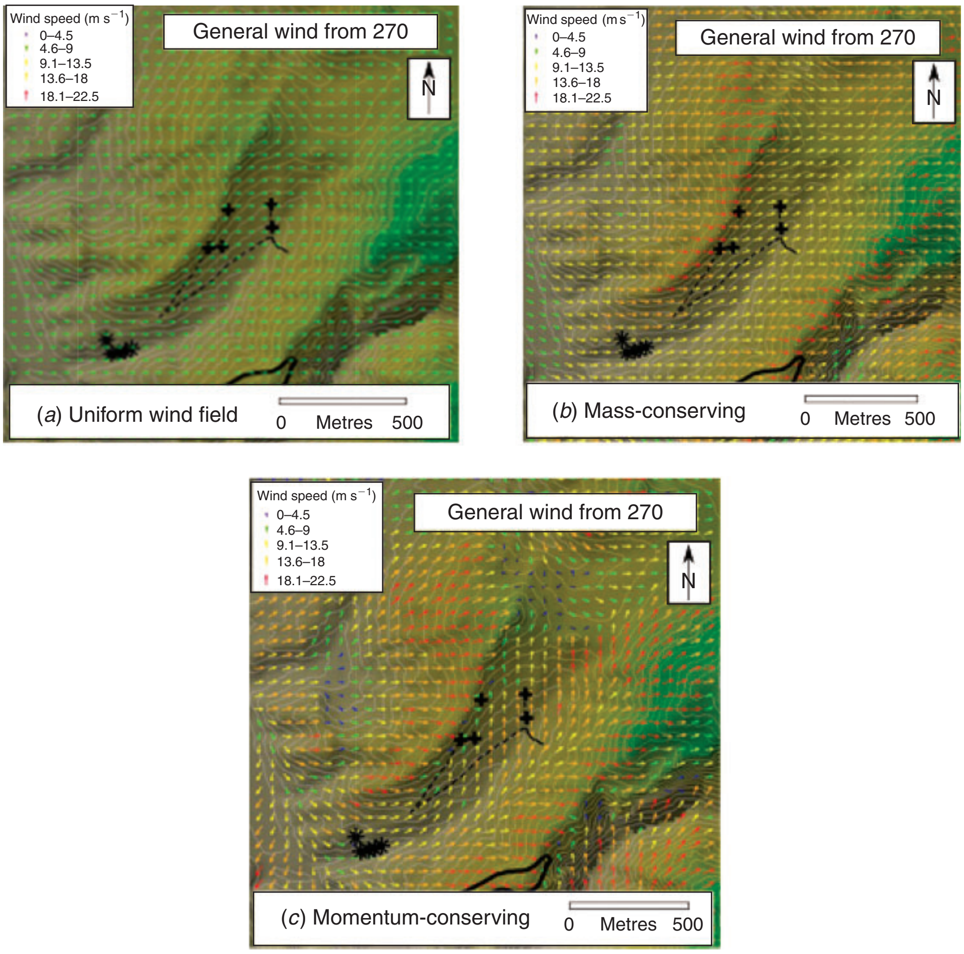

Fig. 6. Wind simulations for the Mann Gulch fire. Wind direction is from 270°. (*a*) spatially uniform wind field, (*b*) mass-conserving wind model, (*c*) momentum-conserving wind model. See caption for Fig. 5 for description of other symbols on the figure.

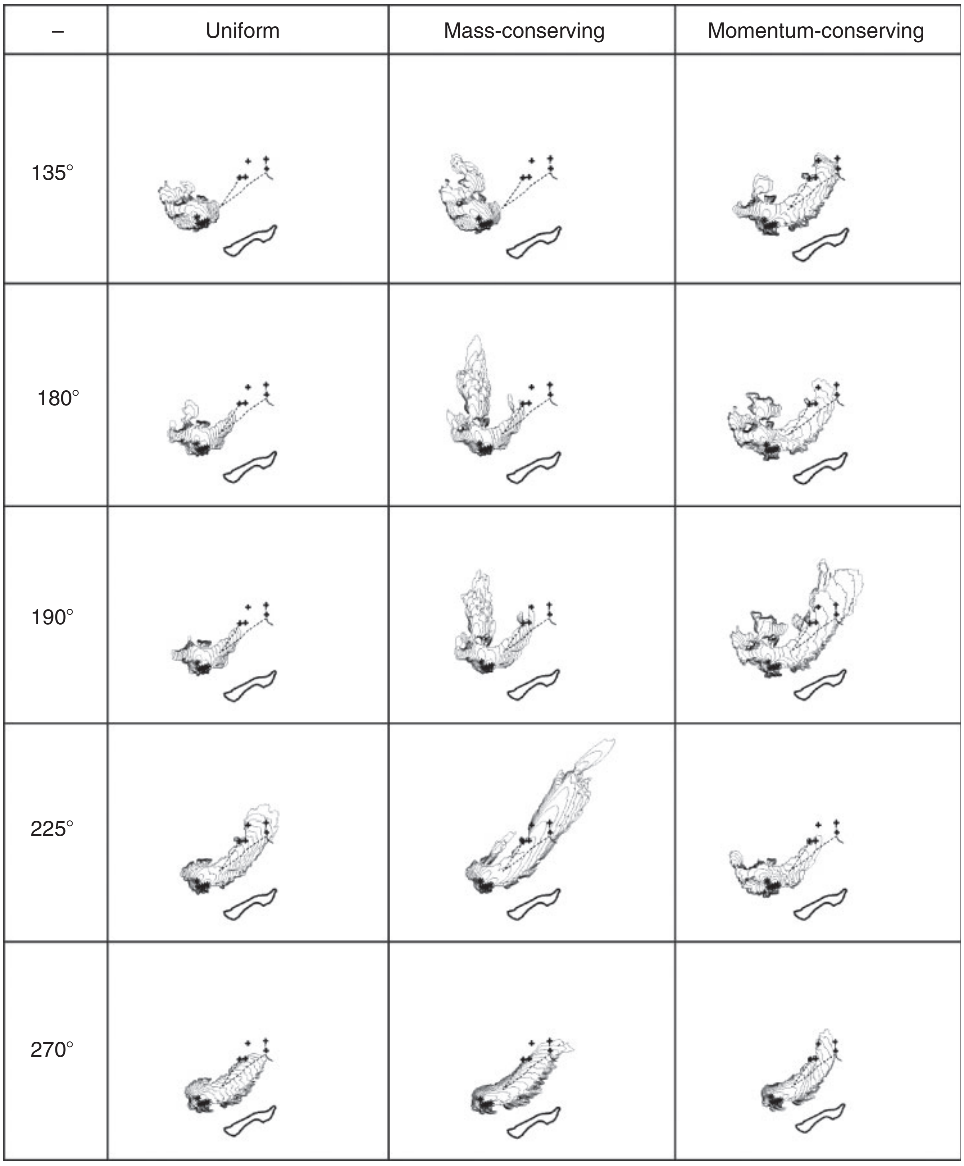

Fig. 7. Fire progression from Mann Gulch simulations. The thin black lines represent the progression of the fire. The simulated progression lines are at 3-min intervals. The thick black line is the estimated perimeter of the fire when the smokejumpers landed; the dashed line is the smokejumpers' path of travel. Other markings are identified in Fig. 5.

testing and demonstration. A significant finding suggested by these simulations is that although large-scale, sophisticated atmospheric flow forecast models account for a much larger set of relevant physical processes, wind simulation models that incorporate a minimum set of physical processes show promise for capturing the primary factors influencing local fire behaviour at the scale of 100–200 m. This is supported by others using similar modelling approaches (Lopes *et al.* 2002). Further improvement could be achieved through the incorporation of additional physics in the wind models, but the wind simulation times and computational requirements would likely then exceed the operational constraints associated with fire management. Models based on a reduced set of physics such as those evaluated here should be used with an understanding of their inherent limitations; for example, their inability to simulate unsteady flows.

Conclusions

Three methods for specifying near surface winds were implemented in three fire growth simulations, two of which were compared against observed fire growth associated with short-term wind events for a range of wind model input wind directions. The wind models were designed to support wildland fire management and thus are subject to well-defined constraints in terms of user expertise, computational requirements and solution time. The comparisons suggested that high-resolution winds can improve fire model accuracy, provided that fire growth model parameters are set appropriately. It also appears that as complexity of the wind model increases the accuracy of the fire growth simulations increases. In operational fire applications, NWS forecast data are often sparse for the fire area and do not reflect local terrain effects on the flow. Therefore, the reduced sensitivity to input direction as shown by the momentum-conserving-based fire simulations for the Mann Gulch and South Canyon fires simulations could be important to fire managers trying to predict fire growth. The utility of high-resolution winds for wildland fire accident investigations, fire management, firefighter and public safety, and emissions monitoring have been documented through their use on hundreds of wildland fires (Butler *et al.* 2006; Stratton 2006; Cruz *et al.* 2012). Current development of the wind-modelling tools is focussed on initialising the high-resolution wind modelling with data from prognostic forecast models[A].

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[A]Users interested in gridded wind data for fire modelling can download the current mass-conserving model (WindNinja) from www.Firemodels.org. At the time of press, WindNinja includes only a mass-conserving solution. Efforts are underway to implement a momentum-conserving solution option in WindNinja, with release expected in 2015. Users interested in momentum-conserving wind solutions can contact the authors of this study for custom simulations using this approach.

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