Visualization and Modeling of Smoke Transport Over Landscape Scales

Glenn P. Forney[1] and William Mell[1]

***Abstract**—Computational tools have been developed at the National Institute of Standards and Technology (NIST) for modeling fire spread and smoke transport. These tools have been adapted to address fire scenarios that occur in the wildland urban interface (WUI) over kilometer-scale distances. These models include the smoke plume transport model ALOFT (A Large Open Fire plume Trajectory model) and WFDS (Wildland-urban interface Fire Dynamics Simulator) for fire spread and smoke transport in the wildland-urban interface. The visualization tool is called Smokeview. In this paper, an overview of the physical basis of the fire spread and smoke transport models will be discussed briefly along with the visualization of characteristic results using Smokeview. A technique will be described for visualizing smoke realistically, and indications will be given how Smokeview can be applied to other fire models.*

Introduction

The National Institute of Standards and Technology (NIST) has developed a suite of validated computational tools for the simulation and visualization of fire spread and smoke transport. These tools have been adapted for addressing fire scenarios that occur over distances of the order of kilometers, in particular, fire scenarios that address the wildland urban interface (WUI) problem. These models include the smoke plume transport model ALOFT (A Large Open Fire plume Trajectory model; Walton and others 2003) and the model WFDS (Wildland-urban interface Fire Dynamics Simulator) for fire spread and smoke transport in the wildland-urban interface (Evans and others 2004; Mell and others 2007). The visualization tool is called Smokeview (Forney and others 2003; Forney and McGrattan 2004). These tools were developed with an emphasis on ease of use on affordable computer platforms. In this paper, the physical basis of the fire spread and smoke transport models will be discussed briefly along with presentation of characteristic results using Smokeview. Smokeview visualizes data in several ways: by animating two-dimensional slices of gas phase quantities such as temperature or smoke concentration, by animating flow vectors and animating surface conditions such as incident heat flux or burning rates at the forest floor and also by animating iso-surfaces showing all places in the simulation scenario where a gas phase quantity takes on a specified value.

Smokeview is capable of rendering smoke and fire realistically using smoke concentrations computed by WFDS. By taking account of smoke properties, visibility can be assessed. We will discuss the potential use of Smokeview for the visualization of predictions from other smoke transport models.

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[1] Research Scientists, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD. Lead author at glenn.forney@nist.gov

Modeling Fire Spread in the Outdoors

Computer modeling and visualization are important tools for understanding many complex processes. Fire behavior is no exception. Fire models range in complexity from simple algebraic correlations for predicting quantities such as flame heights or flow velocities to moderately complex differential equation based zone fire models for predicting quantities spatially averaged over large regions. Both classes of models work well when used appropriately but break down for complicated flows or geometries. For such cases, computational fluid dynamics (CFD) techniques are required.

Computing Fire and Smoke Spread with CFD

The Fire Dynamics Simulator (FDS) has been developed at NIST to simulate the effects of fire and smoke spread (McGrattan 2004; McGrattan and Forney 2004). FDS predicts smoke and/or hot air flow movement caused by fire, wind, and other factors by solving numerically the fundamental equations governing fluid flow, commonly known as the Navier-Stokes equations. The fire model WFDS builds on FDS by adding algorithms needed for solving the wildland interface problem. In particular, algorithms for modeling flame spread on or among the types of materials encountered in the WUI such as grassland, trees, shrubs, and so on. An experimental program is also proceeding to determine important material properties required by the WUI models (Manzello and others 2006).

WFDS is a physics-based fire-atmosphere coupled model that uses a form of CFD known as large eddy simulation (LES) to predict the thermal conditions resulting from a fire. These types of models require significantly more computational resources than the most commonly used fire spread models such as BEHAVE (Andrews and Bevins 1999) and FARSITE (Finney and Andrews 1999), which are semiempirical or empirical. However, there are a number of fire behavior problems, of increasing relevance, that are outside the scope of empirical and semiempirical models. Examples are wildland-urban interface fires, assessing how well fuel treatments work to reduce the intensity of wildland fires, and investigating the mechanisms and conditions underlying blowup fires and fire spread through heterogeneous fuels. WFDS uses approximations to the governing equations of fluid dynamics, combustion, and the thermal degradation of solid fuel. The LES approximation for solving the governing equations is a way of describing the effect of turbulence on the flow field. Turbulence is a phenomenon that causes gases to mix over a wide range of length scales making it hard to replicate with even the fastest computers. The combustion model assumes that fuel and oxygen burn readily when mixed. The fire itself is a heat source term in the governing equations, creating buoyant motion that drives the smoke and hot gases throughout the domain of the simulation. The smoke yield is specified for a given fuel type based on measurements.

The downside of a CFD calculation such as WFDS is that depending on the computational resources, it can easily take days to run. As a result, parallelization techniques become important for splitting the work load among multiple computers, thereby speeding up the calculation and allowing results to be generated in a reasonable time.

Simulation Overview

WFDS, like any CFD model, requires that the scenario of interest be divided into small control volumes called computational cells. The model then computes the density, velocity, temperature, pressure, and species concentration of the mass distribution (gas + particulates) in each cell based on the conservation laws of mass, momentum, and energy. WFDS simulates the spread of the fire by calculating the thermal degradation of the vegetative fuels. This is driven by the radiative and convective heat fluxes from the fire and depends on material properties of the vegetation. The spatial resolution of the simulation depends on the number of cells used to discretize the volume of interest, much like the quality of a digital photograph depends mainly on the number of pixels. The number of cells is ultimately limited by the computing power available and the time available for the calculation. Current PCs limit the number of cells to a few million. Many more cells may be used if calculations are run in parallel by splitting up the problem into parts and solving each part on a different PC. Model users must balance how much detail they want to incorporate with run times required to perform the computation. In general, finer grids result in longer calculations, which produce better results. Ultimately, one reaches a point of diminishing returns where the answer becomes insensitive to the increasing resolution of the grid.

The temporal resolution or time step size is determined from the grid resolution and the flow speed. The time step is chosen by WFDS, so that flow does not cross more than one grid cell during a single time step.

Both FDS and Smokeview would not have been possible without the recent advent of high-speed computers for performing computations, fast video cards for visualizing results and the Internet for exchanging information and ideas. These programs also would not have been possible without the research needed to develop the underlying fire models and the techniques needed to implement these models accurately and efficiently.

While simple line plots are adequate for visualizing the results of simple fire models, more sophisticated techniques are needed for interpreting the massive amounts of data generated by CFD models. This is where visualization tools such as Smokeview, the companion to WFDS, become essential.

Visualizing Smoke

Smokeview displays smoke allowing quantitative assessment using standard visualization techniques such as animated tracer particles that follow the flow, animated shaded 2D and 3D contours that display flow quantities, and animated flow vectors that display flow quantities and direction. Smokeview also visualizes smoke realistically by converting soot density to smoke opacity, displaying smoke as it would actually appear. These visualization techniques highlight different aspects of the underlying flow phenomena.

Visualization is essential at all stages of the process. It is used before a run to verify the correctness of scenario geometry (locations and size of simulation features, for example), during a run to monitor the simulation (ensure boundary flows are behaving as intended), and after the run has been completed to analyze the results.

Smokeview consists of about 70,000 lines of code. Most of it is written in C using standard libraries such as OpenGL (Shreiner and others 2005) and GLUT (Kilgard 1996) for graphics; GD (Web site: http://www.boutell.com/gd/), libpng (http://www.libpng.org/pub/png/), and libjpeg (http://www.ijg.org) for generating image files; and libzip (http://www.gzip.org/zlib/) for compression. A portion of Smokeview is written in Fortran 90 to input data generated by WFDS. The use of portable libraries allows Smokeview to run on many platforms including Windows, and various versions of Unix such as IRIX (for the SGI), Linux, and OSX (for the Macintosh). *(Any mention of commercial products is for information only; it does not imply recommendation or endorsement by NIST.)*

Though Smokeview is usually used to visualize the results of WFDS or FDS simulations it is also used by other models. For example, Smokeview is used to visualize simulation results of the zone fire model CFAST (Jones and others 2004). An earlier version of Smokeview was adapted for visualization of the constituents of concrete during its formation in Concreteview (Bentz and Forney 2000) and molecular dynamics simulations in Molecview (Stoliarov and others 2003). The file formats that Smokeview uses for visualizing data are documented in both the Smokeview (Forney and McGrattan 2004) and FDS (McGratan and Forney 2004) users guide, enabling other fire models to make use of Smokeview as a visualization postprocessor.

Scientific Visualizations

Figures 1, 2, and 3 show simulations of a crown fire spreading left to right from a virgin, untreated, forest stand into a treated stand. The fuel properties in the untreated stand are based on those measured in the black spruce and Jack pine overstory stands in the Northwest Territory of Canada during the International Crown Fire Modeling Experiments (Alexander and others 2004).

Particles—WFDS uses particles as modeling elements to account for heat transfer and momentum drag that occurs during tree burning. This is illustrated in figure 1a. Particles may also be used to visualize the fire and smoke flow. Figure 1b shows a realistic view of the trees.

Slice planes—Smokeview allows animated color shaded contours of calculated gas quantities to be drawn at any horizontal or vertical plane in the simulation. To minimize file output, the user specifies the particular slice planes to be visualized. If disk space is not an issue, then the user may specify the entire 3D volume. Smokeview then allows the user to scroll through the 3D volume of data one slice at a time displaying any horizontal or vertical plane. Figure 2 illustrates temperature contours in a vertical plane through the center of a grassland fire. Temperatures below 100 °C are truncated. Figure 2a shows solid shaded contours while figure 2b shows a vector plot. The data are colored the same way in both cases. Vector animations as illustrated in figure 2b are better than regular slice animations at highlighting flow changes, especially in regions where temperatures are uniform.

Isosurfaces—Smokeview uses isosurfaces to identify where a specified level of a gas phase quantity occurs rather than *how much.* For example, WFDS uses a mixture fraction model to simulate combustion. In this model, there is a critical or stoichimetric mixture fraction value, such that regions greater than the critical value are fuel rich and regions less than the critical value are fuel lean. Burning then occurs, according to the model, on the level surface where the mixture fraction equals this stoichimetric value. Therefore, it is of interest to visualize these locations. This is done using animated isosurfaces.

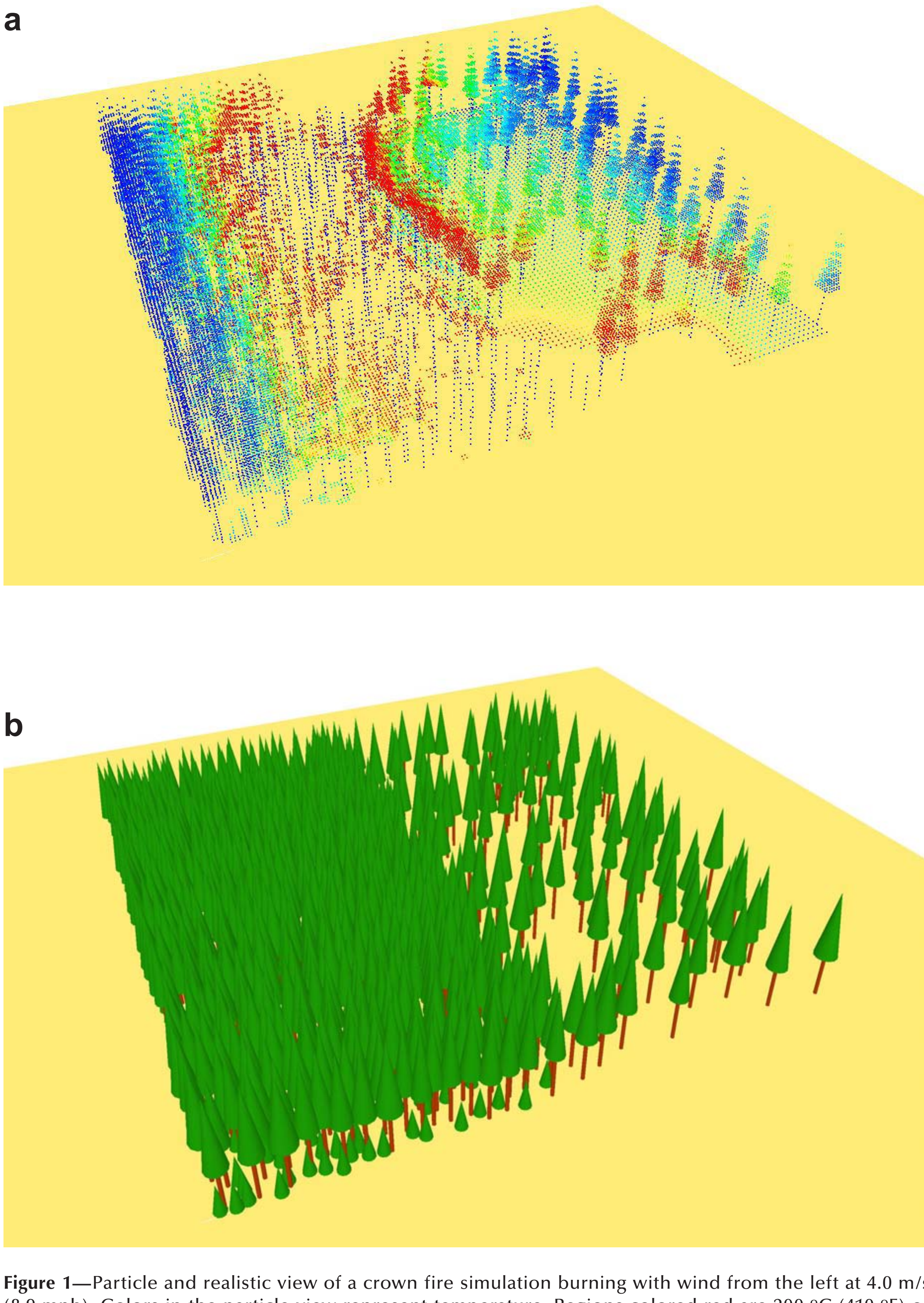

Figure 1—Particle and realistic view of a crown fire simulation burning with wind from the left at 4.0 m/s (8.9 mph). Colors in the particle view represent temperature. Regions colored red are 200 °C (410 °F) or warmer, regions colored blue are about 25 °C (77 °F). Tree section is 50 m on a side. (1a) Trees drawn and modeled using particles. Particles release heat. Particles also drag or slow down air flowing past. (1b) Trees drawn realistically.

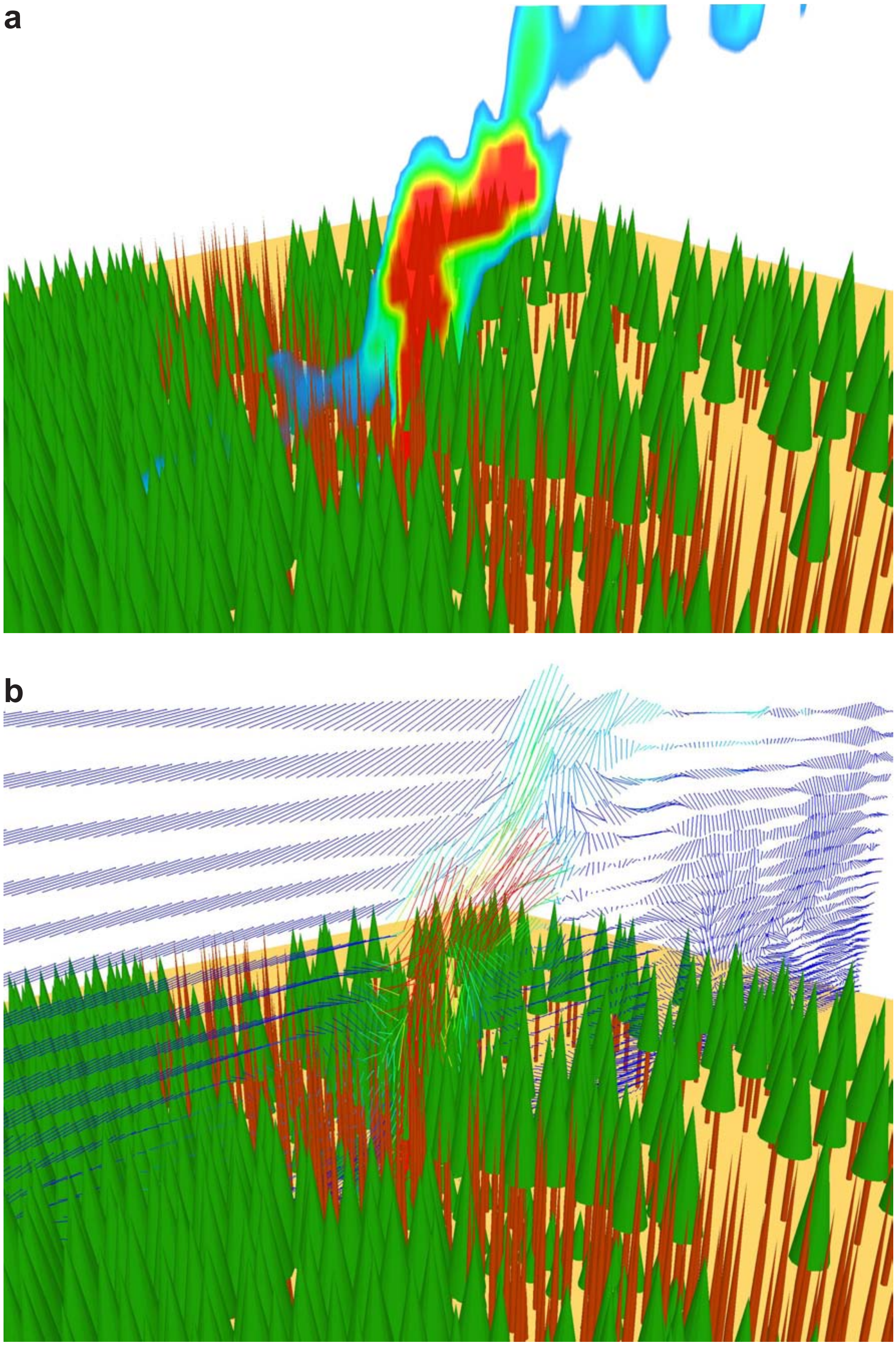

Figure 2—Snapshot of shaded temperature contours and flow vectors through the center of a crown fire simulation with wind velocity boundary condition (from the left) of 4.0 m/s (8.9 mph). Colors represent temperature. Regions (or vectors) colored red are 200 °C (410 °F) or warmer, regions colored blue are about 25 °C (77 °F) . The region in the plot with temperature below 50 °C (122 °F) is hidden. Tree section is 50 m on a side. (2a) Shaded temperature contours. (2b) Colored flow vectors.

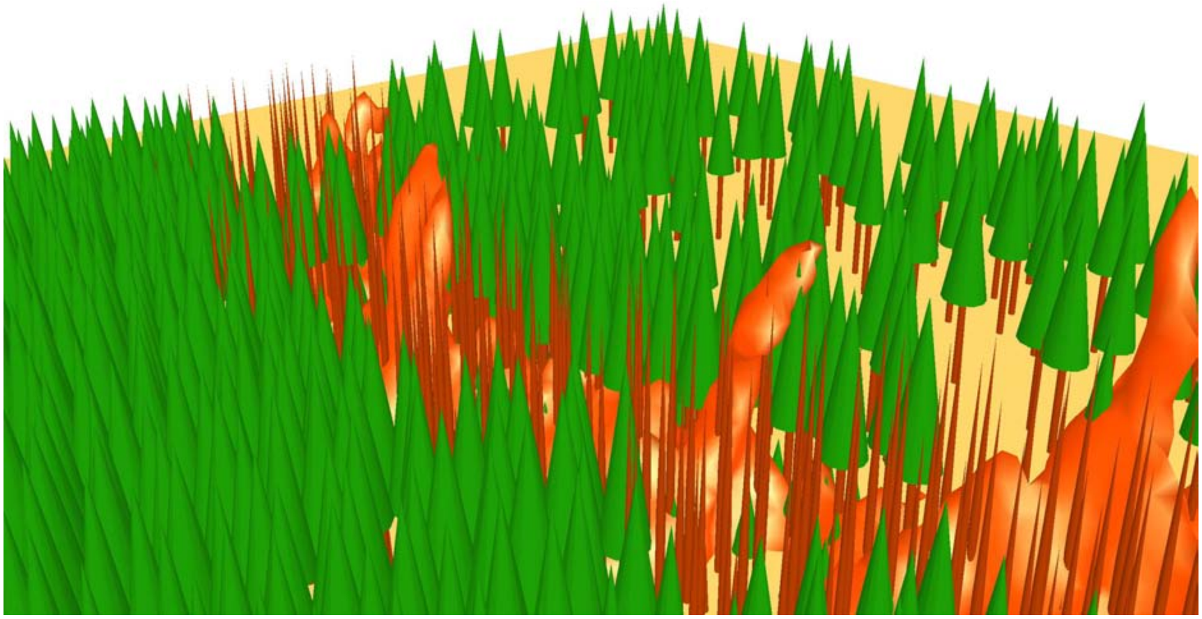

Figure 3—Snapshot of an iso-surface for of stoichimetric mixture fraction, a reasonably accurate surrogate for visualizing flames.

The isosurfaces are generated at each desired time step using a marching cube algorithm (Lorensen and Cline 1987) modified to remove ambiguities. A decimation procedure is used to reduce the number of resulting triangles by collapsing nodes of triangles with large aspect ratios and retriangulating. This makes the isosurface look better and also reduces storage requirements. Figure 3 illustrates the use of iso-surfaces for visualizing the stoichimetric mixture fraction at the same time and view point as seen in figure 2.

Realistic Visualization

Visualizing smoke realistically is challenging for three reasons. The storage requirements for describing smoke throughout the simulation scene at every time step can easily exceed the disk size capacities of present 32 bit operating systems, which would typically be 2 GB. The computation required both by the CPU and the video card to display each frame can easily exceed 0.1 s, the time corresponding to a 10 frame/s display rate. The physics required to describe smoke and its interaction with itself and surrounding light sources is complex and computationally intensive. Approximations and simplifications are required.

Smoke visualization techniques described previously, such as the use of tracer particles or shaded 2D contours are useful for analyzing data quantitatively, but are not suitable for applications where realism is required. Some examples of such applications are using Smokeview as a virtual fire fighter trainer or using Smokeview to examine the obscuration effects of smoke on an outdoor environment.

The approach used by Smokeview for visualizing smoke realistically is similar to that taken in Fedkiw and others (2001) except that interactions with smoke and light are not considered (only the effects of smoke obscuration are visualized). The video hardware is exploited to perform an obscuration calculation by using OpenGL to display a series of partially transparent parallel planes. The planes are chosen from the 3D obscuration data set computed by WFDS to be the ones most perpendicular to the viewer's line of sight. Different plane orientations are chosen in real time as the viewer rotates the scene. The transparencies are computed based on physics using data derived from a WFDS calculation. Vertices in each plane are colored black. The vertices are also assigned an OpenGL α opaqueness parameter. The assigned value depends on the optical smoke thickness, with 0.0 used for completely transparent smoke and 1.0 for completely opaque.

Computing opaqueness—The α values are precomputed by WFDS using Beer's law (Siegel and Howell 2001):

$$\alpha = 1 - \exp(-ks\Delta x) \quad (1)$$

for a particular view direction (down the *x* axis) where Δx is the distance between two nodes, *k* is the soot mass extinction coefficient and *s* is the soot density. Beer's law is an empirical relationship relating light absorption to the material properties of the media the light is traveling through, in this case soot or smoke. Smokeview currently does not consider light scattering effects with smoke.

Adjusting opaqueness—The absorption parameter, α needs to be adjusted when the view direction is not aligned along the axis orthogonal to the viewing planes (as in fig. 4), the distance between adjacent smoke planes changes, or viewing planes are skipped.

Ten million exponential operations per second are required to display smoke with corrected α's at 10 frames per second if the simulation has grid dimensions of 100*100*100. Recent advances in CPU and video hardware makes these types of visualizations possible. These corrections may also be performed in the video card (GPU), resulting in increased display rates since the GPU performs the corrections simultaneously at all or many of the grid nodes rather than one at a time as the CPU would.

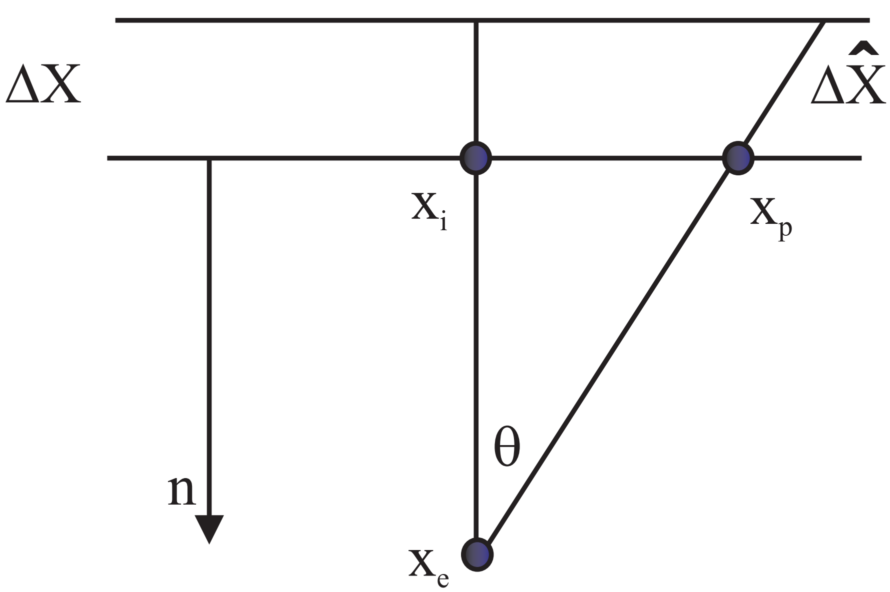

Figure 4—Illustration of the adjustment needed to the opaqueness parameter, α, for non axis aligned views. The α value along the ray containing the $\hat{x}$ segment needs to be larger to account for the longer path length.

The α obscurations are precomputed using the distance *Δx* between adjacent planes along the x-axis. The adjusted $\hat{\alpha}$ expressed in terms of $\Delta\hat{x}$ is given by

$$\hat{\alpha} = 1 - \exp(-ks\Delta\hat{x}) \tag{2}$$

Equations 1 and 2 may be used to solve for $\hat{\alpha}$ in terms of α to obtain

$$\hat{\alpha} = 1 - (1-\alpha)^{\Delta\hat{x}/\Delta x} \tag{3}$$

after noting that

$$1 - \hat{\alpha} = \exp(-ks\Delta\hat{x}) = \exp(-ks\Delta x)^{\Delta\hat{x}/\Delta x} = (1-\alpha)^{\Delta\hat{x}/\Delta x}$$

The computation of equation 3 is expensive because the exponential is computed at each grid node for every time step. In addition, numerical cancellation may occur for α close to zero leading to loss of significant digits. Both problems may be solved by expanding equation 3 in a Taylor series and keeping only the first few terms:

$$\hat{\alpha} \approx \alpha r - \frac{a^2}{2} r(r-1) + \frac{a^3}{2} r(r-1)(r-2)$$

where $r = \sec(\theta) = \Delta\hat{x} / \Delta x = \left\| x_p - x_e \right\| / n \cdot (x_p - x_e)$, *n* is the unit vector normal to the current plane being drawn, α is the angle between the view direction and the normal vector *n*, x_e is the observers position, and x_p is the vertex being drawn (along the view direction). These terms are illustrated in figure 4.

When planes are skipped equation 3 may be simplified. In particular when every second plane is skipped, $\Delta\hat{x} / \Delta x = 2$, so that equation 3 simplifies to

$$\hat{\alpha} = 1 - (1-\alpha)^2 = 2\alpha - \alpha^2$$

The video hardware uses α values contained in the smoke planes to obscure the background much like a camera uses a neutral density filter to darken a scene. Extending the analogy, Smokeview uses one *neutral density filter* (numerically) for each plane of smoke data. On a node by node basis then, each smoke plane obscures the current image stored in the OpenGL back buffer by the amount (1-α) to form a new back buffer image. A simplistic description of one step of this process is given by

new buffer image = (1-α) * old buffer image

This process is repeated for each smoke plane. Figure 5 illustrates this process for smoke and fire spread over a large grassland fire simulated by WFDS. The fuel properties are based on those measured in grassland plots during experiments conducted in Australia. A further description of the fuels and simulations is in Mell and others (2007).

The visualization is performed by displaying a series of partially transparent planes. For illustration, these planes are made more conspicuous (in fig. 5a) by skipping smoke planes (displaying every third plane) and orienting them along the x axis. Figure 5b shows the visualization as it would normally appear with all slice planes shown and oriented toward the viewer.

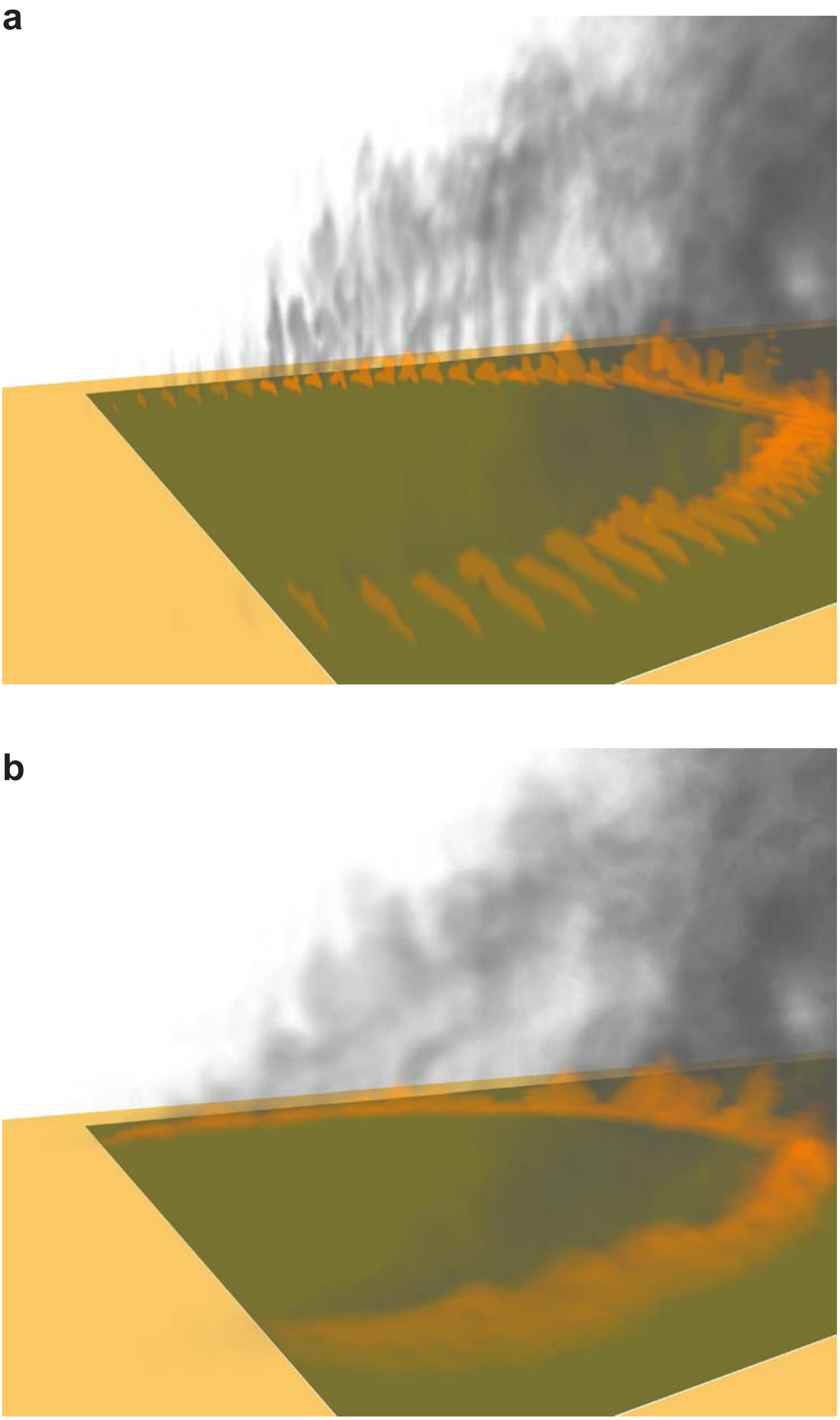

Figure 5—Realistic visualization of a large grass fire simulated using WFDS. Planes in the top image are drawn to be conspicuous by skipping two out of every three planes and by aligning planes along the x axis. All planes in the bottom image are displayed (none are skipped) and they are aligned to be closest to perpendicular of all possible plane orientations. (5a) Slices skipped and oriented along x directions. (5b) All slices shown and oriented toward viewer.

Summary

Smokeview is used to visualize data simulated by WFDS, the NIST wildland fire dynamics simulator. Smokeview uses several techniques to visualize data, some scientific and some realistic. The realistic technique uses the video hardware found on modern computers to convert soot densities computed by WFDS to opacities displayed on the computer screen. The local values of obscuration are computed by WFDS for all grid nodes using soot density, grid spacing, and the soot mass extinction coefficient appropriate for visible light and the fuel being burned. This is a one time computation. Smokeview, on the other hand, integrates these local values along the line of sight each time the view position or direction changes and for each frame of data.

Smokeview is a scientific visualization tool that has been adapted to display data for several types of applications and it may be adapted to display data simulated by fire models used to solve other aspects of the WUI problem.

Additional Information

“Fire on the Web” (http://fire.nist.gov) contains resources related to fires including images and movies of real fires along with measured heat release data, software for modeling fire flow, and links to NIST publications related to fire. Information on the fire modeling software FDS and Smokeview may be found at http://fire.nist.gov/fds. Further information about the wildland urban interface adaptation of FDS (WFDS) may be found at http://www2.bfrl.nist.gov/userpages/wmell/public.html.

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