SMOKE PLUMES FROM IN-SITU BURNING OF CRUDE OIL

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ABSTRACT: *Several regions in the United States have begun the process of obtaining preapproval to use in-situ burning as a remediation method for oil spills. The Building and Fire Research Laboratory of the National Institute of Standards and Technology (NIST) under the sponsorship of the Minerals Management Service has conducted a research program to study various aspects of this problem. One result of this program has been the development of a numerical model to predict the downwind concentration of smoke particulate and other combustion products from a large oil fire. To assess the accuracy of this model, data from three sets of experimental burns have been compared to model simulations run under similar meteorological conditions. The tests are (1) the Newfoundland Offshore Burn Experiment (NOBE), August 1993; (2) the Alaska Clean Seas Burning of Emulsions, September 1994; and (3) the U.S. Coast Guard/NIST Meso-scale Burn Series, October 1994. The model compared favorably with the experiments, increasing the confidence in numerical modeling as a tool to develop guidelines on safe distances from in-situ burns.*

Several regions of the United States, Canada, and Europe are presently evaluating the feasibility of using burning as a remediation method for large oil spills. The National Institute of Standards and Technology (NIST), under the sponsorship of the Minerals Management Service and the Alaska Department of Environmental Conservation, has conducted a research program over the past decade to assess the burning characteristics of large crude oil fires on water (Evans *et al.*, 1993). The program has consisted of laboratory and mesoscale measurements of burning and emission properties of various heavy fuels, as well as a theoretical effort to model the smoke plume and predict the downwind concentration of various combustion products whose emission factors are measured from large-scale experiments. The model has been named ALOFT for "a large outdoor fireplume trajectory." In previous reports, the model was referred to as the large eddy simulation (LES) model because much of the numerical methodology originated with enclosure fire models developed at NIST.

A particular concern of local authorities who are considering in-situ burning is the possibility of exposing populations to particulate concentrations in excess of ambient air quality standards. Thus, in processing the results of the model, special attention is given to the downwind and lateral extent of ground-level particulate concentrations in excess of 150 μg/m^3 averaged over 1 hour. Although no formal guidance is available concerning safe levels of short-term exposure to particulate emissions from oil fires, 150 μg/m^3 averaged over 24 hours is the upper level established under air quality control regulations in Alaska. Calculations performed for the state of Alaska showed that, for a variety of meteorological conditions typical of the northern and southern coasts of Alaska, hour-averaged particulate concentrations found at the ground downwind of a fire consuming about 75 kg (600 bbl) of crude oil per hour would not exceed 150 μg/m^3 (hour averaged) beyond 5 km (McGrattan *et al.*, 1993).

To assess the accuracy of these model predictions, we will compare data from several sets of field experiments with model predictions. The experiments are the Newfoundland Offshore Burn Experiment (NOBE), conducted by Environment Canada in August 1993, the Burning of Emulsions Test, conducted by Alaska Clean Seas (ACS) in September 1994, and a series of diesel fuel burns conducted by NIST at the U.S. Coast Guard Fire and Safety Test Detachment, Mobile, Alabama, in October 1994.

Mathematical model

A detailed description of the ALOFT model is given by Baum *et al.* (1994). The model consists of the conservation equations of mass, momentum, and energy that describe the steady-state, convective transport of heated gases and combustion products introduced into the atmosphere by a steadily burning fire and blown by a uniform ambient wind. The fire itself is not modeled, but rather the plume of smoke that emanates from it. The heat release rate and smoke yield of the fuel are required as inputs. The local meteorological conditions that must be provided are the wind speed, the fluctuation in wind direction, and the temperature stratification of the atmosphere. Figure 1 shows the results of a typical calculation. The structure of the rising plume, characterized by the formation of two large counter-rotating vortices, must be captured by the numerical scheme because it controls the entrainment of air into the hot plume. The height to which the plume ultimately rises and the rate at which the pollutants are dispersed are very much a function of the initial plume structure. The plume structure of an actual burn is shown in Figure 2.

The ALOFT model differs from most of the atmospheric dispersion models in use today because it is a deterministic rather than an empirical model; that is, the approach taken is to solve the governing equations of motion directly rather than rely on empirical formulas that approximate the extent of the dispersion. These empirical models typically assume the pollutant of interest to be Gaussian distributed in the plane perpendicular to the direction of the prevailing wind. The parameters defining the distribution are estimated from experiments. Unfortunately, the problem of in-situ burning of crude oil is inappropriate for these types of models for three reasons: (1) the nature of the "source" is different from what is normally assumed, a smokestack; (2) the heat release rate of the source is well beyond those considered in industrial process applications and thus outside of the experimental parameter range; and (3) the plume dispersion patterns are not necessarily Gaussian, and many of the time-averaging arguments used in conventional dispersion models do not apply for burns of at most several hours in duration. As will be seen from the results of lidar measurements taken at both the Newfoundland and Mobile experiments, the plume structure is very sensitive to local atmospheric conditions.

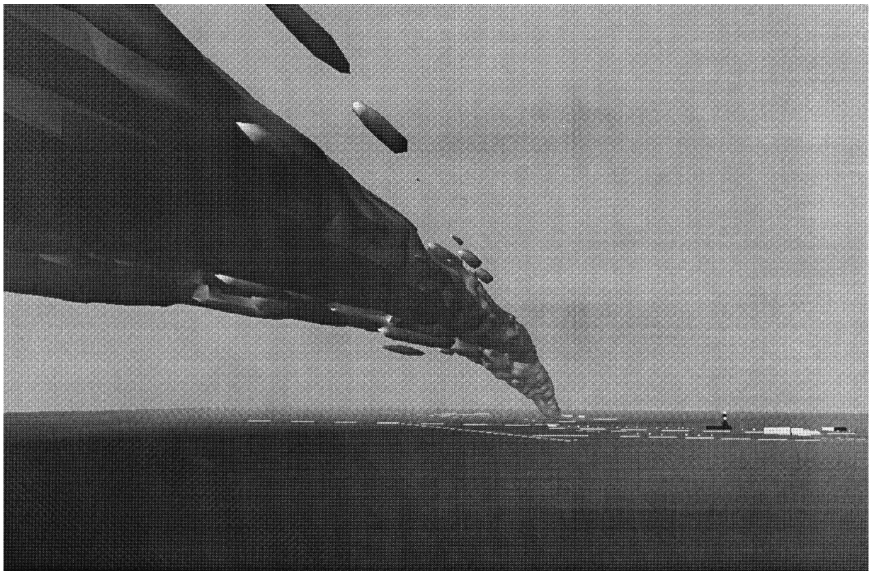

Figure 1. View of a simulated smoke plume as seen from downwind

Figure 2. Photograph taken from about 200 m downwind of the Newfoundland Offshore Burn Experiment (NOBE) showing the two large counter-rotating vortices that characterize the structure of the rising smoke plume

The Newfoundland Offshore Burn Experiment

The Newfoundland Offshore Burn Experiment (NOBE) provided an enormous amount of data regarding in-situ burning of oil at sea (Fingas *et al.*, 1995). The experiment consisted of two burns of crude oil conducted off the coast of St. John's, Newfoundland, on August 12, 1993. Most of the sampling of the chemical species produced by the burning was done relatively close to the fire. However, the University of Washington's Cloud and Aerosol Research Group performed airborne measurements of the smoke plume from the two burns at distances up to 20 km downwind of the fire. Of particular importance to the present study are the lidar measurements of the plume cross section and the real-time monitoring of the CO_2 level in the plume.

Lidar measurements were performed during the second burn. Details of the analysis are given by Ross *et al.* (1996). For this burn, it was reported that 28.9 m^3 (182 bbl) of crude oil of density 843.7 kg/m^3 was burned in 1.3 hours. Even though substantial fluctuations in burning rate were observed, for the purposes of modeling the plume it was assumed that the burning rate was constant at 5.2 kg/s (140 bbl/hr). On the basis of previous work with various types of crude oils (Walton *et al.*, 1993), the heat release rate of the fire, based on the amount of oil consumed, was estimated to be about 200 MW. The smoke yield for the burn was measured by the team from NIST to be approximately 15% (Walton *et al.*, 1994). Atmospheric temperature soundings taken from the University of Washington airplane and from the NIST tethered blimp show a temperature inversion from about 100 to 175 m in altitude, accompanied by a shift of roughly 30 to 40 degrees in the direction of the wind. The wind speed at the ground was about 5 to 6 m/s, increasing to about 8 m/s a few hundred meters up.

Figure 3 displays cross sections of the simulated plume at downwind locations that approximately match those taken by the University of Washington airplane (Figure 4). The effect of the shift in the wind direction at about 120 m in altitude is obvious in both the simulated and the actual plume cross sections. There is reasonably good qualitative and quantitative agreement between the two for a distance of about 6 km from the fire. This assessment is based on the overall lofting height of the plume, its lateral spread due to the wind shear, and the concentrations observed in both the experiment and the simulation. A more rigorous comparison would not be meaningful because the actual plume was very much affected by the change in burning rate that sent puffs of smoke higher when the burn rate increased. The model simulation is based on the assumption that the fire is burned

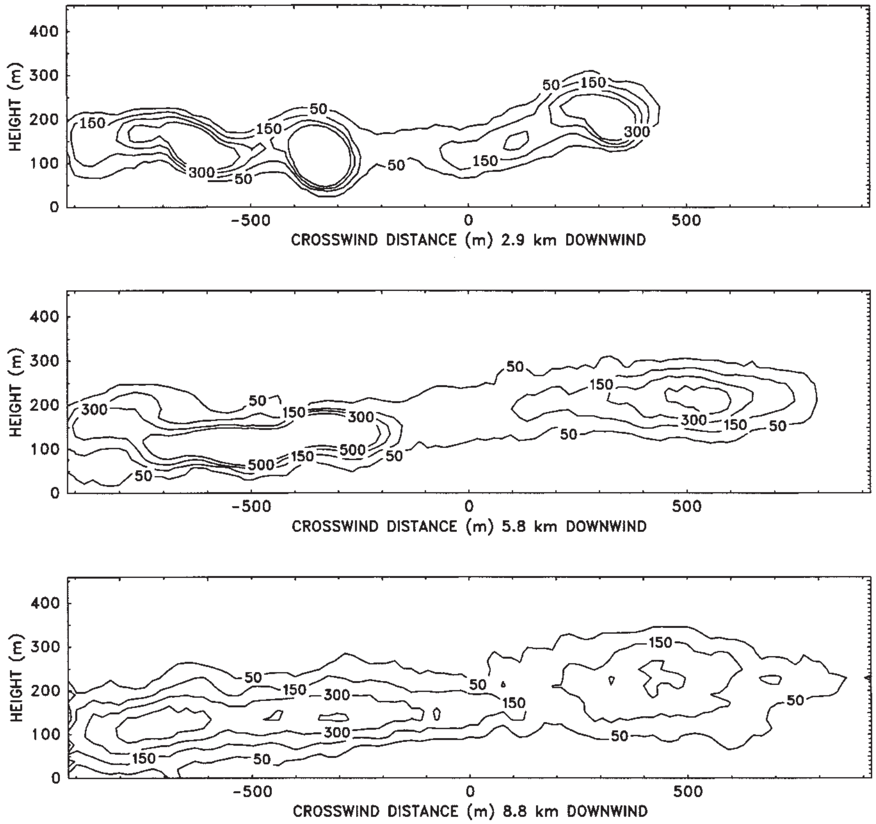

Figure 3. Cross-sectional slices of the simulated smoke plume from the second NOBE burn. Shown are particulate concentration contours of 50, 150, 300, and 500 µg/m^3 at three locations downwind corresponding to where lidar measurements were taken. The vertical-length scale indicates height above sea level, and the horizontal scale indicates the distance from the assumed plume centerline.

steadily, and thus represents a time-averaged, rather than instantaneous, description of the plume. Beyond about 6 km from the fire, the simulation fails to predict the increased lofting of the actual plume to a height of about 700 m. It was observed that the plume initially rose to a height of about 200 m, leveled off for about 5 km, and then gradually rose to a height of about 600 m after 20 km. The centerline of the simulated plume reached a height of about 250 m, but does not exhibit this gradual rise. Changes in the burning rate and solar radiation, both of which are not accounted for in the simulation, are most likely responsible for the increased lofting. This example points out the limitation of any predictive dispersion or meteorological model. Large-scale patterns and trends can be predicted, but small-scale details cannot.

In addition to lidar measurements, the University of Washington team made a number of other measurements. Of interest to this study are measurements of CO_2. Plume particulate concentrations may be derived either by quantifying lidar cross section data as shown in text preceding, or by measuring the excess CO_2 and backing out the particulate concentration based on the smoke yield and the elemental carbon mass fraction of the fuel. Direct measurements of excess CO_2 made while flying the airplane along the centerline of the plume have been used to estimate the concentration of particulate matter. Taking the smoke yield to be 15% (from the NIST tethered blimp measurements) and the elemental carbon mass fraction of the fuel to be 0.8664, it is estimated that 1 ppm excess CO_2 corresponds to a particulate concentration of 103 µg/m^3. Direct measurements of excess CO_2 in the smoke plume from the airplane show volume fractions decreasing to about 1.5 ppm (the equivalent of 150 µg/m^3 particulate) at about 16 km downwind of the burn. The quantified lidar images are consistent with this finding. The model calculation predicts that plume particulate concentrations in excess of 150 µg/m^3 extend slightly farther than 20 km downwind. The discrepancy in the two estimates is not surprising, given the enhanced plume dispersion of the experiment due to the unexpected lofting. Also, the comparison is based on only one pass of the airplane along the plume centerline, which may not account for the maximum concentration. Indeed, the model predicts, and visual sightings confirm, the existence of counter-rotating vortices that are generated by the fire and that entrain a substantial fraction of the particulate. Thus, it is not necessarily true that the maximum concentration of particulate would be found along the centerline of the plume. In-situ measurements of the plume cannot account for its complex structure, and thus a better means of measuring particulate concentration would be through the use of integrated techniques, such as the lidar measurements discussed in text preceding.

Alaska Clean Seas burning of emulsions experiment

In early September 1994, Alaska Clean Seas conducted at its Fire Training Ground in Prudhoe Bay, Alaska, three mesoscale burns to determine the feasibility of burning emulsified oil. An aerial photograph of one of the burns is shown in Figure 5. Each burn consisted of burning an oil mixture within the confines of a fire-resistant circular boom that floated in a pit filled with water. The boom diameter was roughly 9 m, and the rectangular pit was roughly 20 m by 30 m. The first and third burns consumed emulsions of saltwater and 17.4% evaporated Alaskan North Slope (ANS) crude. Emulsion breakers were applied to these mixtures. The second burn consumed fresh ANS crude. Heat release rates for the three burns were estimated to be 55, 186, and 98 MW, respectively. The burning rates of oil, not emulsion, were 31, 115, and 56 bbl/hr, respectively. Each burn lasted about 45 minutes. The mass flux of particulate was based on a smoke

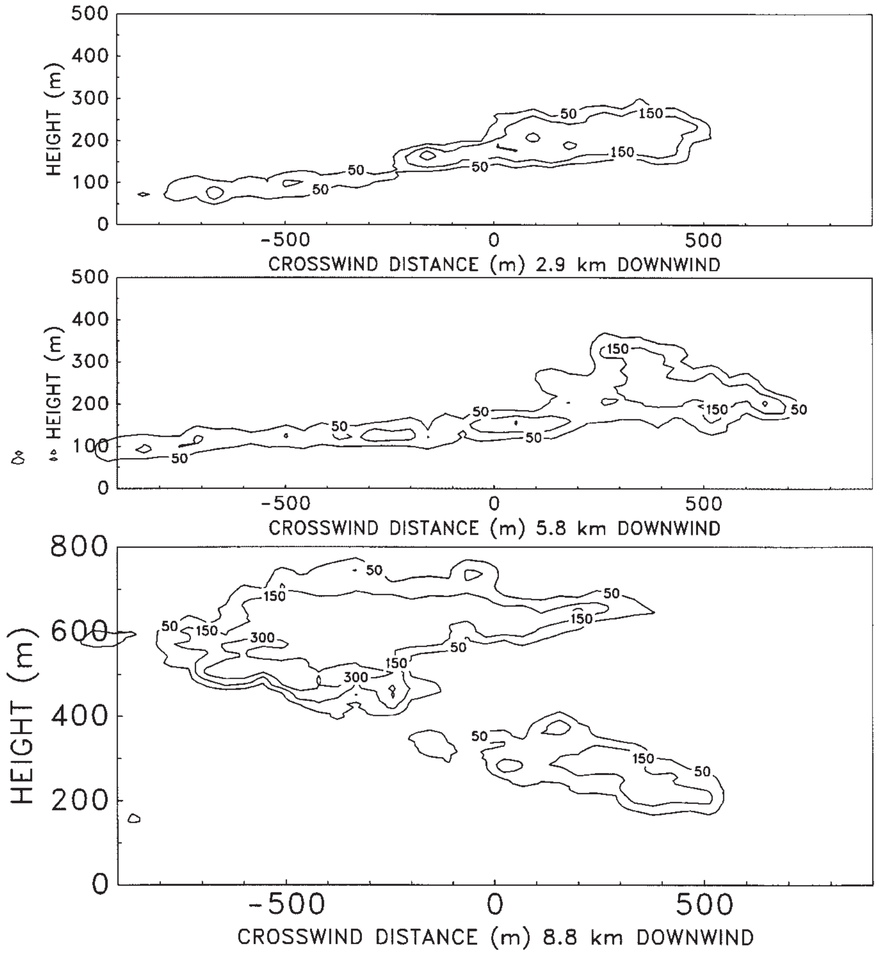

Figure 4. Cross-sectional slices of the actual smoke plume from the second NOBE burn. Shown are contours of particulate concentration at 50, 150, and 300 µg/m³. The crosswind scale indicates relative distances, and the origin was chosen to compare with the simulation. (Courtesy of the University of Washington Cloud and Aerosol Research Group.)

yield (mass of particulate per unit mass of oil burned) for ANS crude of 11.6%.

At the request of the Alaska office of the U.S. Environmental Protection Agency, the EPA's Emergency Response Team (EPA/ERT) came to Prudhoe Bay with 12 MIE real-time aerosol monitors (RAM-1). These instruments employ a sensing principle that is based on the detection of near-forward electromagnetic radiation in the near infrared. The amount of scattered radiation detected quantifies particulate and aerosol concentrations. The twelve instruments were set out on tripods and spread out in rows of three or four at distances ranging from 1 to 5 km from the burn site. The deployment strategy varied from burn to burn, depending on the weather conditions and the terrain over which the plume was expected to loft. The instruments were set to sample every second and then log the 5-second average. Global positioning instruments recorded the locations of the individual devices. Atmospheric temperatures, wind speeds, and wind directions were measured with a weather station suspended from a small tethered blimp, which was deployed just after the burns were completed. Details of the measurements may be found in the report by McGrattan *et al.* (1995).

Figure 6 summarizes the results of the experiments, showing the model prediction of ground-level particulate concentration versus the actual measurements made in the field. The field measurements were averaged over the time of the burn. Neither the model predictions nor the RAM data were uniform in space or in time, due in part to random fluctuations in wind direction, convective cells that are not accounted for in the model, small terrain effects, and unsteady burning of the fuel. Nevertheless, the agreement between the time-averaged model predictions and field measurements is quite good, showing particulate concentrations ranging from 0 to 80 µg m^{-3} along the narrow path over which the plume is lofted. In addition to ground-level instruments, a small airplane was hired to fly in the vicinity of the plume and to record plume positions at various times, as well as to photograph the burn site and the plume. According to flight track data, the plume from the first burn rose to a height of about 550 m and the plume from the second burn rose to about 400 m. These measurements are in very good agreement with model predictions based on atmospheric profiles obtained with a tethered blimp and a helicopter. The visibility on the day of the third burn was very limited, and all aircraft were grounded.

Mesoscale diesel fuel burns, Mobile, Alabama

Three mesoscale burns of no. 2 diesel fuel were conducted by NIST at the U.S. Coast Guard Fire and Safety Test Detachment facility on

Figure 5. Aerial view of second Alaska Clean Seas emulsion burn experiment, Prudhoe Bay, Alaska, September 1994

Little Sand Island in Mobile Bay, Alabama, in October 1994 (Walton *et al.*, 1995). The burns were conducted in a 15.2-m-square by 0.61-m-deep steel burn pan. Water filled about 0.5 m of the pan, and diesel fuel was added to fill the rest. The no. 2 diesel fuel was obtained from a commercial vendor. Each burn lasted between 15 and 20 minutes, and the fuel was consumed at a rate of about 400 bbl/hr for each burn.

The first burn was ignited in the afternoon on October 23. The winds were very calm, and as a result the smoke plume rose high into the cloud layer and changed its direction from that of the ground. This plume holds some interest from a qualitative point of view, but it is not possible to compare against the ALOFT model because the details of the wind field are too complex to be simulated, and no temperature or wind sounding was available. In any event, there was certainly no mixing back to the surface because the plume rose more than a kilometer into the atmosphere.

The second and third burns, conducted in the morning and afternoon of October 26, are more of interest from a model validation standpoint. On this day, the wind was blowing steadily from the north, and the smoke plumes from both burns lofted over the western shore of Mobile Bay and out into the Gulf of Mexico. A team from SRI, International, of Menlo Park, California, performed airborne lidar measurements of the smoke plumes (Uthe *et al.*, 1995). The instrument was flown above the smoke plume and generated cross-sectional images of the plume in vertical planes perpendicular to the direction of the wind at various distances downwind of the fire. The lidar was operated at a pulse rate of 10 Hz, with each pulse producing backscatter profiles at wavelengths of 0.53 and 1.06 μm. Figures 7 and 8 present the lidar images for roughly the first 10 kilometers from the burn site.

Clearly visible in each sequence of images is the top of the mixing layer, which separates the earth's turbulent boundary layer below from the free atmosphere above. The mixing layer is characterized by turbulent motion generated by surface friction and vertical heat transfer from the warm ground to the cooler air above. For the morning burn, the height of the mixing layer was about 450 m, and in the afternoon it had risen to about 700 m. Although a temperature sounding could not be obtained on that day, it is clear that the top of the mixing layer at both times of the day corresponded to a temperature inversion and shift in wind direction. The wind was blowing out of the north at ground level, but apparently shifted to become northeasterly above the mixing height. This wind shear is very noticeable because most of the smoke particulate is concentrated in that narrow band. The smoke that mixes down to the surface does so at the interface between land and water, in a process known as fumigation.

The ALOFT model was run to try to simulate both the morning and afternoon burns. Because no sounding was available, the temperature and wind profiles had to be estimated from ground measurements and visual observations of the general state of the lower atmosphere. Figures 9 and 10 summarize the ground-level prediction of smoke particulate concentration from the model, along with the maximum values of the lidar measurements for each pass of the aircraft above the plume. The particulate concentrations are derived from the lidar signatures by assuming constant backscatter-to-density and extinction-to-density ratios. The latter quantity was derived by Ross *et al.* (1996). As in the analysis of the Newfoundland lidar data, it is impossible to replicate every meteorological detail reflected in the instantaneous lidar measurements. Instead, it is assumed that the wind fluctuation and vertical convective motion are random processes. In this way, the plume structure and the local meteorology can be described in sufficient detail to produce predictions in the neighborhood of the measured concentrations.

Discussion

It has been estimated that a 500-foot (150-m) fire boom towed in a U-shape configuration could easily provide enough oil area to sustain a burn eliminating about 715 bbl/hr (Allen and Ferek, 1993). Of all the experiments discussed within this paper, the smoke plumes from the Mobile burns, although of short duration, are most representative of those that can be expected from an actual in-situ burn, for two reasons. First, the burning rate of 400 bbl/hr is probably a reasonable rate to expect from an actual burn. Second, the experiments were conducted in a coastal environment; thus the atmospheric conditions represented by the lidar images are very typical of what one can expect in the event of a near-shore in-situ burn. The results of both the modeling effort and the lidar measurements showed that even though an inversion layer was present, the plume penetrated it, and as a result less smoke mixed back to the surface. There is no guarantee, of course, that the plume will always penetrate an inversion layer, and in those instances ground-level concentrations could be higher.

In summary, peak concentrations of ground-level smoke particulate for all the burns discussed in text preceding never exceeded 100 μg/m^3,

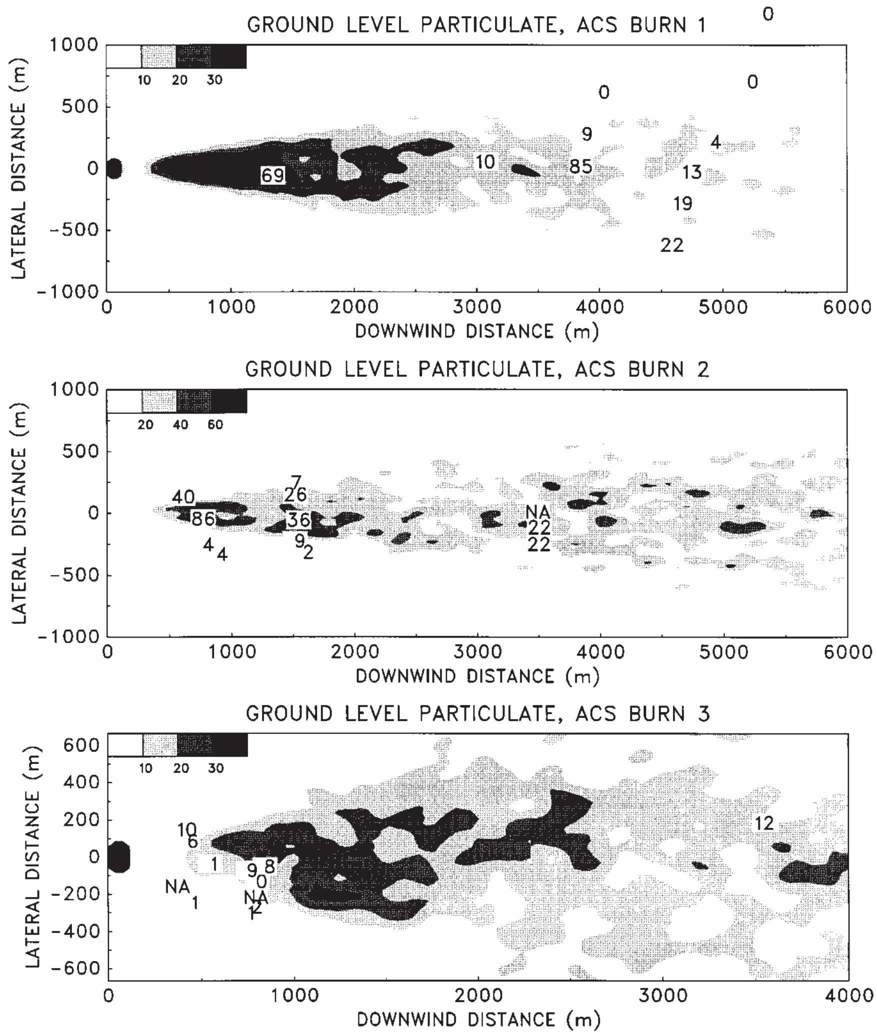

Figure 6. Predicted ground-level particulate concentrations from the ALOFT model (*shaded contours*) along with actual time-averaged RAM data for the three ACS emulsion burns (*numerical labels*). The model results are inherently time-averaged. The fire itself is at the origin of the coordinate system (*left*). All concentrations are given in units of µg m^{-3}.

and in most cases were well below that level. It should be emphasized, however, that these experiments were conducted in reasonably good weather conditions, and in each instance, complex terrain was not a factor. Work to determine the effect of rough terrain, especially in areas like the Pacific Northwest and Alaska, is under way now at NIST.

Conclusion

The results of the experiments presented here increase the confidence in the numerical predictions of plume structure, trajectory, and composition. The comparison of predicted versus measured particulate concentration is very encouraging, given the uncertainties in the input data for the fire and weather conditions. In fact, the model predictions were based on very limited meteorological information—wind speed, wind variation, and temperature stratification only. This is important for two reasons. First, local meteorological data for regions of interest are often very limited. Second, if the numerical model is to be used effectively for a wide variety of conditions, it must not depend on empirical input parameters fine-tuned for a particular situation.

As far as the field measurement techniques are concerned, these experiments have provided a wealth of information on how to monitor emissions from large burns. Unlike conventional air monitoring, where the source, such as a power plant, is expected to generate pollutants over a long period of time, an in-situ burn will typically last a few hours. High-volume samplers are difficult to position and cannot collect enough particulate in that short period of time; hence the need for reliable, portable, real-time aerosol monitors. For the purpose of model verification, lidar measurements have the most potential because they can capture the overall plume structure rather than sparse point measurements. The drawbacks of this technique are that they are expensive, and that the measurements are difficult to quantify.

Needless to say, all of the tools to track and measure smoke plumes from large crude oil fires have their advantages and disadvantages. However, a combination of large-scale experiments and numerical models that have been tested against such experiments, such as ALOFT, will provide response planners with much needed information and the ability to consider situations for which experiments have not, or cannot, be performed.

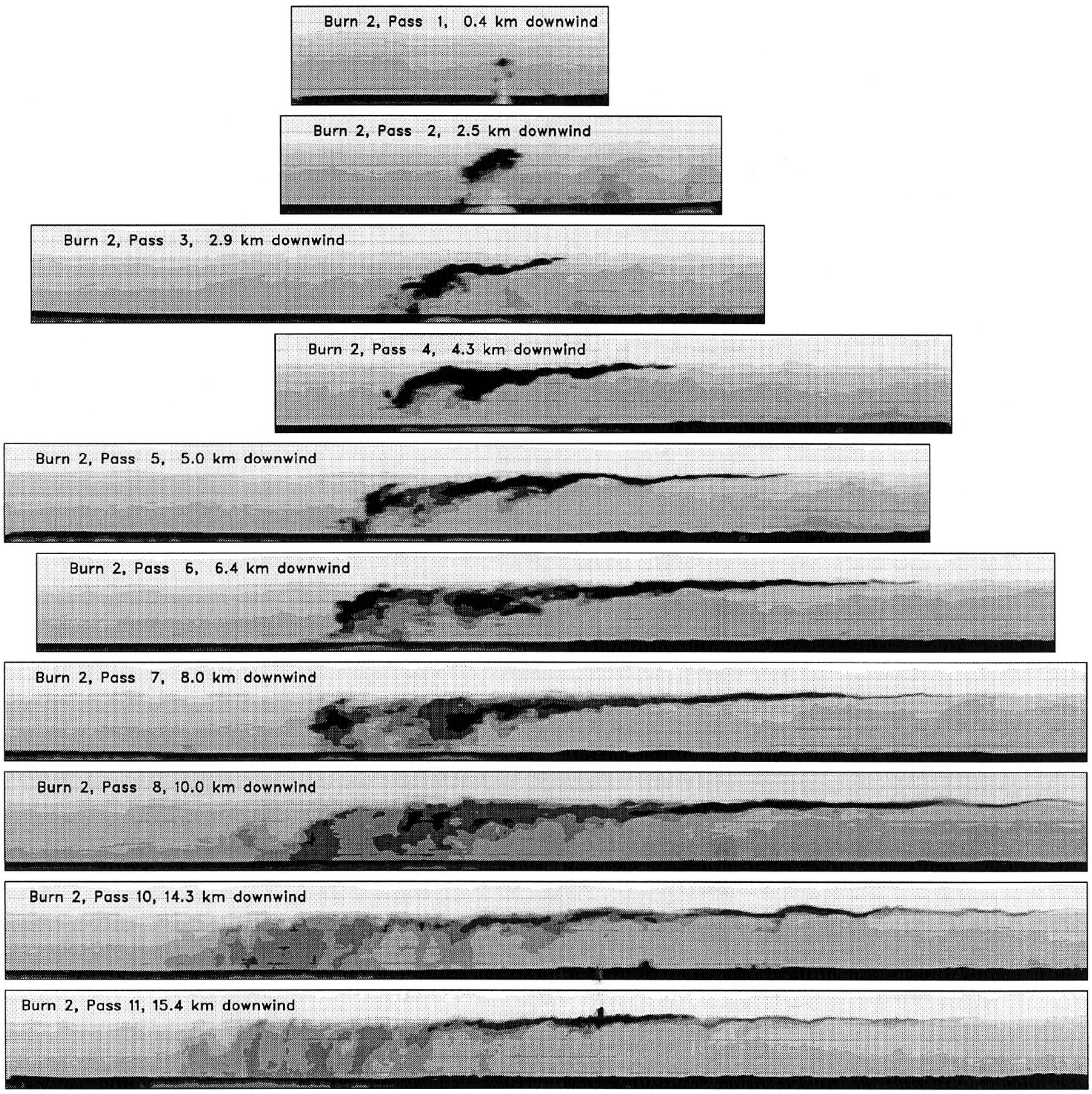

Figure 7. Lidar images of the plume cross section for the morning burn of October 26, 1994, Mobile Bay. These images correspond to vertical planes that are *perpendicular* to the direction of the wind. The elongated nature of the cross section is due to the wind shear at about 450 m above the surface. The grayscale indicates total particulate concentration, and the horizontal lines are separated by 150 meters. The horizontal and vertical lengths are identically scaled, with the vertical dimension 900 m. Note that background particulate and aerosol levels are represented by the horizontal layers extending the width of the frame.

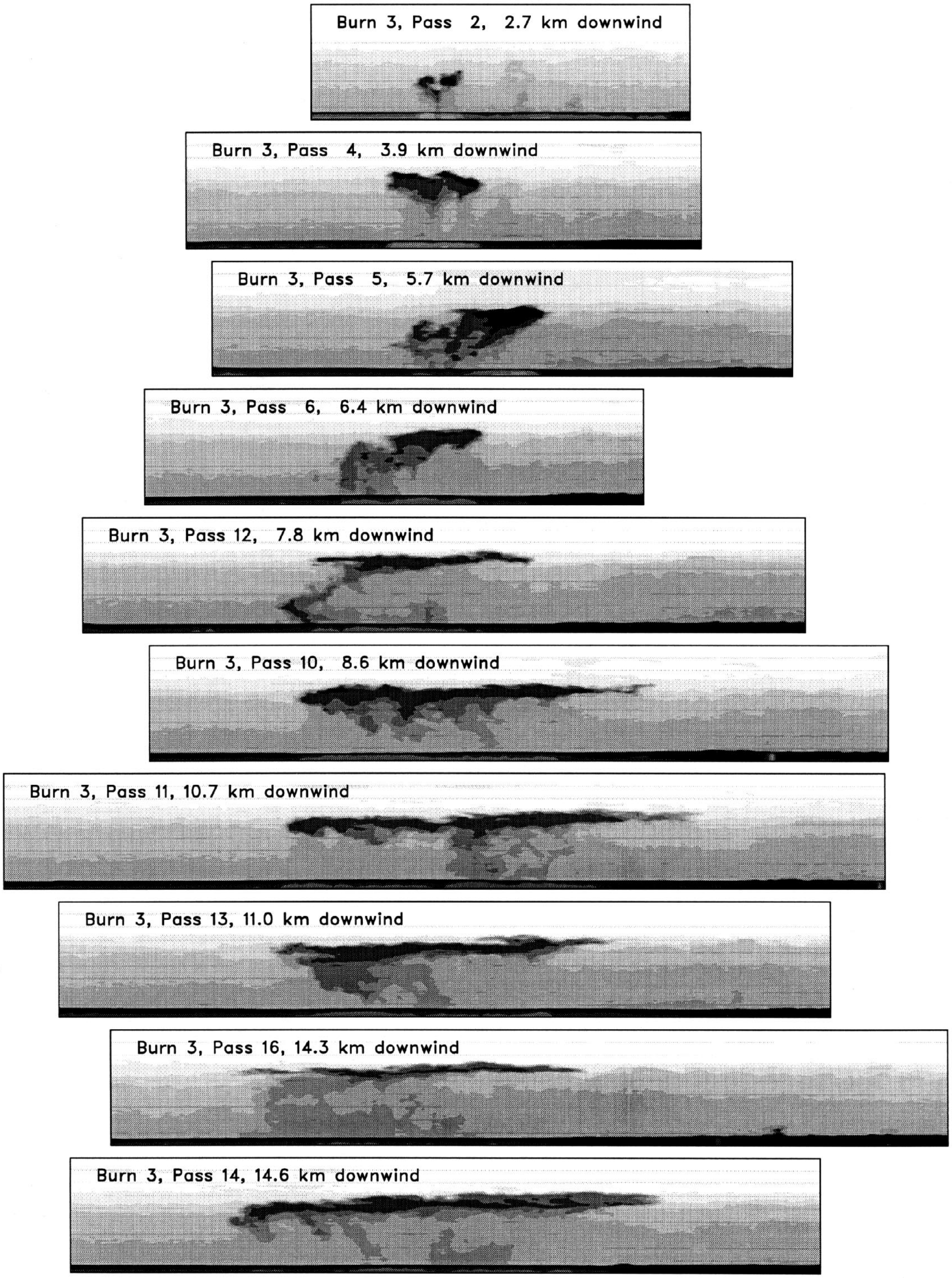

Figure 8. Lidar images of the plume cross section for the afternoon burn of October 26, 1994, Mobile Bay. These images correspond to vertical planes that are *perpendicular* to the direction of the wind. The elongated nature of the cross section is due to the wind shear at about 700 m above the surface. The grayscale indicates total particulate concentration, and the horizontal lines are separated by 150 meters. The horizontal and vertical lengths are identically scaled, with the vertical dimension 1350 m. Note that background particulate and aerosol levels are represented by the horizontal layers extending the width of the frame.

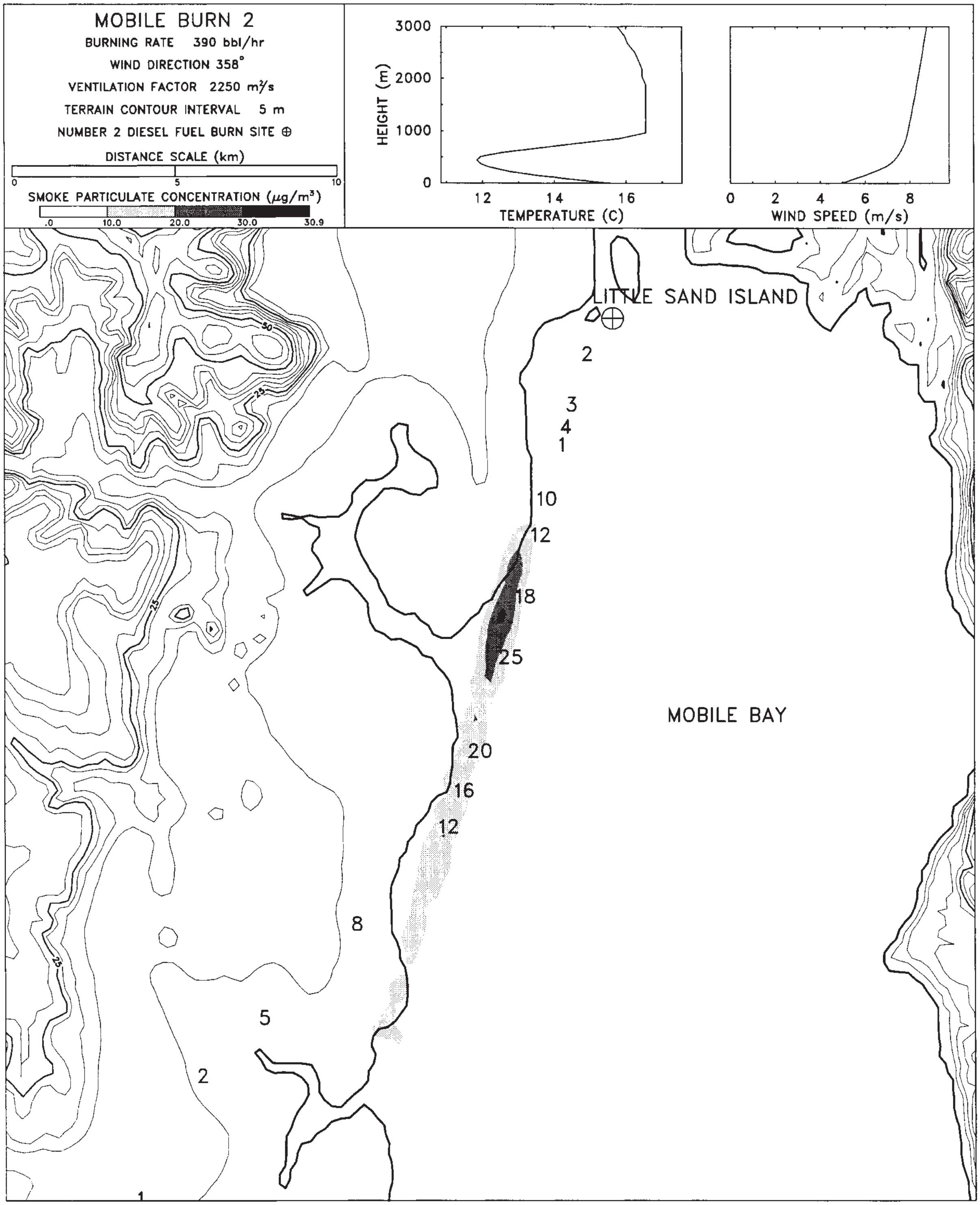

Figure 9. Ground-level particulate concentration for the morning burn of October 26, 1994, in Mobile Bay. The shaded contours represent (time-averaged) model predictions, and the larger numbers represent near ground peak values of the quantified (instantaneous) lidar signatures for each pass of the aircraft. The ventilation factor is merely the height of the mixing layer multiplied by the wind speed, and is used as a rough indicator of atmospheric stability.

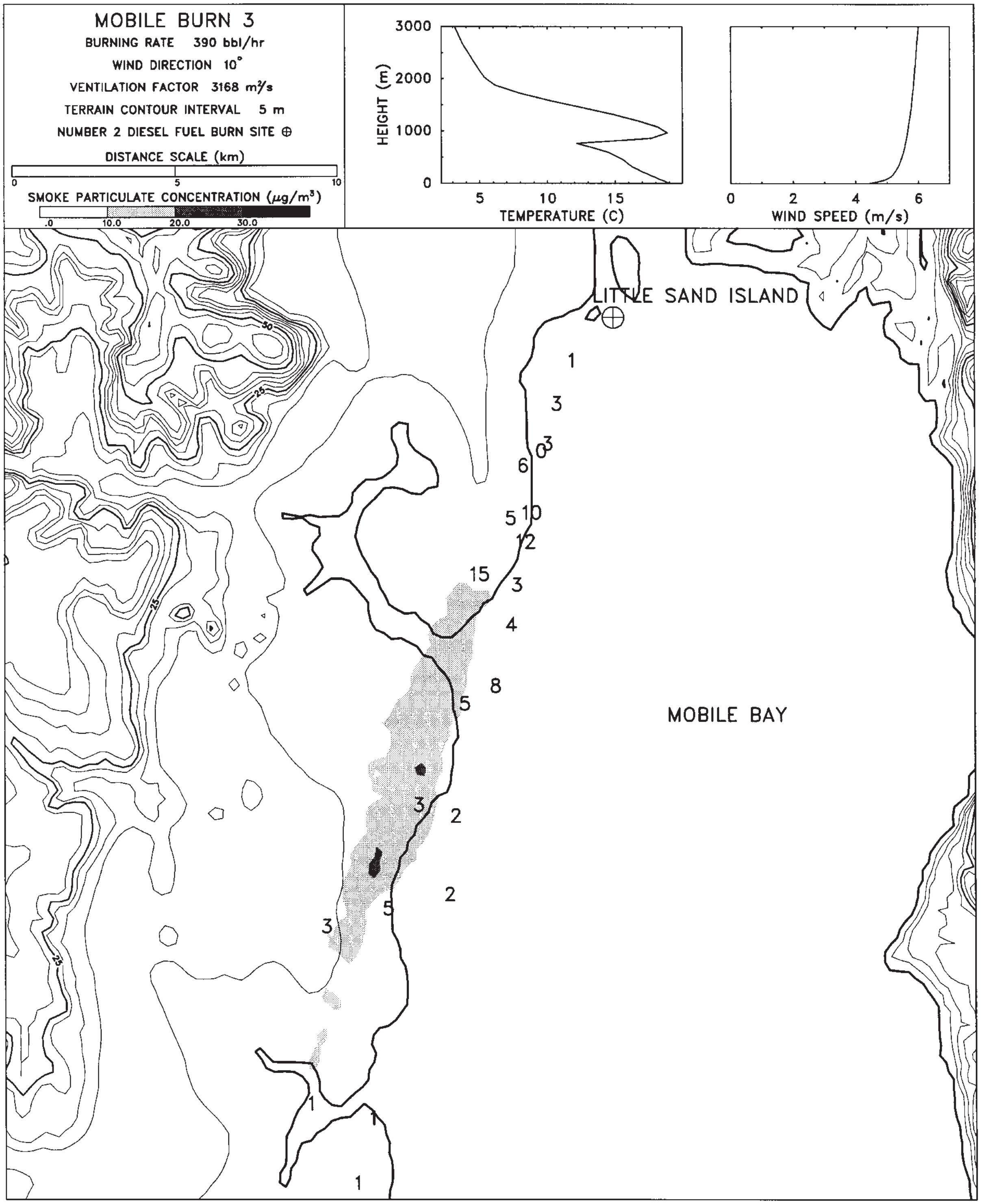

Figure 10. Ground-level particulate concentration for the afternoon burn of October 26, 1994, in Mobile Bay. The shaded contours represent (time-averaged) model predictions, and the larger numbers represent near ground peak values of the quantified (instantaneous) lidar signatures for each pass of the aircraft. The ventilation factor is merely the height of the mixing layer multiplied by the wind speed, and is used as a rough indicator of atmospheric stability.

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