NIST Special Publication 935

In Situ Burning of Oil Spills Workshop Proceedings

New Orleans, Louisiana, November 2-4, 1998

William D. Walton and Nora H. Jason, Editors

Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8644

February 1999

U.S. Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Gary R. Bachula, *Acting Under Secretary for Technology*
National Institute of Standards and Technology
Raymond G. Kammer, *Director*

Sponsored by:
U.S. Department of the Interior
Bruce Babbitt, *Secretary*
Minerals Management Service
Cynthia L. Quaterman, *Director*

NOTICE

The statements and conclusions of this report are those of the authors and do not necessarily reflect the views of the National Institute of Standards and Technology.

COVER

U.S. Coast Guard and Minerals Management Service sponsored fire-resistant oil spill containment boom performance test using a non-commercial test boom at the Coast Guard Fire and Safety Test Detachment, Mobile, AL, August 1997. William D. Walton, Photographer.

ISBN No. 1-886843-03-1
National Institute of Standards and Technology Special Publication 935
Natl. Inst. Stand. Technol. Spec. Publ. 935, 114 pages (February 1999)
CODEN: NSPUE2

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1999

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402-9325

SMOKE PLUME TRAJECTORY MODELING

K.B. McGrattan
National Institute of Standards and Technology
Gaithersburg, Maryland 20899 USA

SUMMARY

A combination of numerical modeling and large scale experimentation has yielded a tremendous amount of information about the structure, trajectory and composition of smoke plumes from large crude oil fires. A numerical model, ALOFT (A Large Outdoor Fire plume Trajectory), has been developed at NIST to predict the downwind concentration of smoke and other combustion products. The model is based on the fundamental conservation equations that govern the introduction of hot gases and particulate matter from a large fire into the atmosphere. The model has been used to estimate distances from fires under of variety of meteorological and topographic conditions where ground level concentrations of smoke and combustion products fall below regulatory threshold levels.

BACKGROUND

Buoyant windblown plumes have been studied since the early 1960s. A summary of the early work together with a useful bibliography is given by Turner[1]. For summaries of more recent work see Turner[2] and Wilson[3]. Most of the models described in these works are integral models, where the profiles of physical quantities in cross-sectional planes perpendicular to the wind direction are assumed, together with simple laws relating entrainment into the plume to macroscopic features used to describe its evolution. A great many of the models in use for air quality assessment simply use Gaussian profiles of pollutant density. Of the available models, the ISCST3 (Industrial Short Complex, Short Term)[4], the CTDMPLUS (Complex Terrain Dispersion Model PLus algorithms for Unstable Situations)[5], the Offshore and Coastal Dispersion (OCD) model[6] or the CALPUFF model[7] could be used to estimate the dispersion of combustion products from *in situ* burning. The ISCST3 model is a popular Gaussian model designed to predict short-term (hours, days), short-range (1 km to 10 km) concentrations of pollutants from industrial sources. The related model CTDMPLUS considers more complex terrain. The OCD model was developed to assess the impact of offshore emissions on the air quality of coastal regions. It features added algorithms to account for atmospheric conditions unique to the coastal environment. The CALPUFF[7] model is not a Gaussian model; rather it tracks "puffs" of pollutants through a temporally and spatially changing atmosphere. The CALPUFF model still uses empirical plume rise formulae and simplified rules to track the pollutants over terrain features such as hills and mountains.

The potential shortcomings of these types of models are that they were designed for typical industrial sources, like smokestacks, that are much smaller in terms of energy output than an oil fire. The plume from an *in situ* burn of oil will rise higher into the atmosphere, and it is difficult to predict the rise based on empirical correlations. If the plume rise is not calculated correctly, substantial errors in downwind concentration can result. In the case of smokestack emissions, the plume does not rise appreciably high, reducing the uncertainty of the results. For this type of problem, the Gaussian models can be expected to give a reasonable answer. However, if the plume originates in a pool fire with little initial velocity, the dynamics of the fire-induced flow field must be included in the simulation. Simple empirical expressions, such as the those described by Briggs[8], often include entrainment parameters calibrated for different source characteristics, but these usually do not encompass the regime of large, buoyancy-dominated plumes such as those produced by burning large amounts of a liquid fuel.

THE ALOFT MODEL

Most of the assumptions required by integral models can be removed by taking advantage of the enormous advances in computational fluid dynamics that have occurred since most of these models were developed. As part of the process of evaluating the feasibility of using *in situ* burning as a remediation tool for large oil spills, the National Institute of Standards and Technology (NIST), under the sponsorship of the Minerals Management Service (MMS) and the Alaska Department of Environmental Conservation (ADEC), has developed a numerical model, ALOFT (A Large Outdoor Fire plume Trajectory), to predict the concentration of smoke and other combustion products downwind of a large fire. The original intent of the effort was to solve a simplified form of the equations of motion that govern the introduction of smoke and hot gases from a large fire into the atmosphere. It was assumed that the smoke plume was blown by a non-zero wind over relatively flat terrain (e.g., the sea surface or a flat coastal area). This version of the model is now referred to as ALOFT-FT™ (Flat Terrain)[9,10]. The flat terrain assumption is crucial, for it leads to the assumption that the windward component of the flow of smoke and hot gases from the fire *is* the prevailing wind, and the numerical problem is reduced to solving for the fire-induced components of velocity and temperature in a plane perpendicular to the prevailing wind. From a computational point of view, this simplifies the problem tremendously and allows for well-resolved computations of the plume dynamics as it rises and levels off in the atmosphere. High resolution in this case refers to the fact that motion on length scales of 5 m to 10 m is captured directly.

Initial calculations of the ALOFT-FT model were performed in 1993, and the results are documented in References [11,12]. In processing the results of the model, special attention was given to the downwind and lateral extent of ground-level particulate concentrations in excess of 150 $\mu g/m^3$ averaged over one hour. For meteorological conditions typical of the northern and southern coasts of Alaska, the calculations showed that hour-averaged particulate concentrations found at the ground downwind of a single continuous burn of a boomful of oil would not exceed 150 $\mu g/m^3$ beyond 5 km.

In follow-up reports[13,14], measurements from three mesoscale burn experiments were compared with ALOFT-FT predictions. The first experiment, the Newfoundland Offshore Burn Experiment (NOBE), was conducted by Environment Canada in August, 1993. The second, the Burning of Emulsions Test, was conducted by Alaska Clean Seas (ACS) in September, 1994. The third was a series of burns at the US Coast Guard Fire and Safety Detachment in Mobile, Alabama. For each series of burns, ALOFT-FT was run for the recorded meteorological and burn conditions, and the results were compared with data collected in the field. For all three large scale field experiments, the agreement between model and experiment was very favorable, and greatly increased the confidence in the numerical model.

The State of Alaska has asked EPA Region 10 to approve the use of the ALOFT model for predicting ground level particulate matter concentrations from oil spill control fires in regions of relatively flat terrain in Alaska. The environmental consulting firm EMCON Alaska, Inc., conducted a performance evaluation of the ALOFT model on behalf of the Alaska Department of Environmental Conservation (ADEC), and submitted their study to EPA Region 10 for review. The quantitative performance evaluation showed that the ALOFT model provides more accurate predictions of ground level particulate matter from oil fires. Compared to CALPUFF, the ALOFT model predictions showed lower absolute fractional bias and greater statistical correlation with the particulate concentration measurements that were made downwind of five experimental burns[15].

Presently, ALOFT-FT™ is available for public use, running under the Windows95®, Windows98® and WindowsNT® operating systems[16]. Documentation of the model is available on-line.

COMPLEX TERRAIN

The ALOFT model has been extended to scenarios involving complex terrain and multiple burns. The uniform wind assumption is no longer valid when the plume is to be tracked over complex terrain. Many regions in Alaska where burning might occur are characterized by complex terrain. In the region near Valdez, mountains rise several thousand meters within a few kilometers of the shore. With this new capability, more realistic, site-specific scenarios can be evaluated. ALOFT-CT™ (Complex Terrain) still makes use of the plume rise methodology employed by ALOFT-FT because the original simplification of the governing equations can be exploited to compute the rise of the plume until its stabilization height is reached. Then, the three-dimensional governing equations can be solved to provide a wind field over the complex terrain.

The extension of the model to incorporate complex terrain justifies the original decision to solve the fundamental equations of motion that govern the transport of the smoke and hot gases from the fires. The increased complexity of the problem makes it more difficult to apply conventional empirical models because the amount of field data with which to calibrate an empirical model to account for arbitrary terrain is very limited, plus the built-in assumptions of such a model are too simplistic to describe the plume as it is transported over a complex landscape. Because the ALOFT model solves the fundamental conservation equations that describe the plume structure and trajectory rather than relying on simplistic assumptions, it is a very flexible tool that can be adapted with confidence to increasingly complicated scenarios.

SAMPLE ALOFT CALCULATIONS

Consider the three-dimensional views of two simulations of smoke plumes originating in the Valdez Narrows, shown in Figure 1. The great difference in the plume trajectories, and the ground level concentration as well, is due to the difference in meteorological conditions. The temperature lapse rate in the first case is very nearly adiabatic (i.e., the temperature decreases with height at a rate of about 7°C/km). This essentially rids the atmosphere of the effects of the density stratification which tends to suppress vertical motion induced by terrain obstacles. Thus, in the first case where the atmosphere is neutrally stratified, the terrain plays less of a role in the plume's trajectory. Contrast this with the bottom figure. Here the atmosphere is very stable, and the temperature near the ground increases with height. Vertical motion is suppressed, forcing the air to flow around rather than over the terrain obstacles. Indeed the plume winds its way through the various passageways between the larger mountain peaks, leading to greater concentrations near the surface (see Figure 2). An excellent description of stratified flow past three-dimensional obstacles is given in Reference [17].

DOWNWIND SMOKE CONCENTRATION ESTIMATES

The calculations performed with the ALOFT model for various weather conditions and locations can be generalized and used to estimate the distance from a fire beyond which ground level concentrations of combustion products fall below regulatory thresholds. The combustion product most likely to violate ambient air quality standards is particulate, and the guideline recommended for *in situ* burning is 150 µg/m^3 (PM10) averaged over one hour.

The two most important factors determining this distance are the terrain height and the mixing layer depth *relative* to the elevation of the burn site. The mixing layer depth is the depth of the atmospheric boundary layer, which can be thought of as the cloud height. Taking a 0.044 m^3/s (1,000 bbl/h) burn as an upper limit for a single fire, 130 g/kg as the particulate emission factor, and 150 µg/m^3 as the hour-averaged concentration threshold, Table 1 lists the maximum distance as a function of terrain height and mixing layer depth. The mixing layer depth is loosely correlated with the temperature lapse rate, and the wind speeds considered were in the range from 1 m/s to 12 m/s. Note that the first row of the table corresponds to relatively flat terrain.

Table 1. Distance from a fire consuming 0.044 m^3/s (1,000 bbl/h) beyond which the hour-averaged ground level concentration of PM10 falls below 150 $\mu g/m^3$. These distances are expressed in units of kilometers (1 mi ≈1.61 km). Terrain Height and Mixing Layer Depth are relative to the altitude of the burn site. Modifications to these distances to account for different fire sizes and PM standards can be made according to the formula given by Equation (1).

Terrain Height (m)	**Mixing Layer Depth (m)**				
	0--100	**100--250**	**250--500**	**500--1,000**	**>1,000**
0--25 ("Flat Terrain")	5	4	3	2	1
25--250	10	8	6	4	3
250--500	15	12	10	8	5
>500	20	17	15	12	10

The maximum distance estimates can be modified to account for changes in the fire size, emission factor, concentration threshold, offshore burns, and multiple burns. If the given burn scenario calls for something other than a single fire on land consuming 0.044 m^3/s (1,000 bbl/h), and the ground level particulate criteria is something other than 150 $\mu g/m^3$ of PM10, then the distance from Table 1, D_{table}, should be modified according to the following formula:

$$D = D_{table} + 7\ln\left[\left(\#\ \text{of burns}\right)\frac{150}{\rho_c}\frac{EF}{130}\left(\frac{BR\ (bbl/h)}{1,000\ (bbl/h)}\right)^{\frac{1}{3}}\right] + \left(d - d_{eq}\right)\ km \quad (1)$$

The critical hour-averaged concentration ρ_c should be expressed in units of $\mu g/m^3$. The new U.S. Environmental Protection Agency (EPA) National Ambient Air Quality Standard (NAAQS) for particulate calls for 65 $\mu g/m^3$ for PM2.5 as well as the current PM10 standard of 150 $\mu g/m^3$. Emission factors for various PM sizes are reported in Reference [14]. The value 130 g/kg is for PM10; 82 g/kg for PM2.5. The Burning Rate, BR, is expressed in units of bbl/h *per fire* (1 bbl/h = 4.4×10^{-5} m^3/s). It is assumed that in the case of multiple burns, all the fires are of comparable size. Note that the Burning Rate, BR, can be expressed in terms of the burn area, burning rate or heat release rate as long as the value of the denominator (here given as 1,000 bbl/h = 0.044 m^3/s) is given in equivalent units. The distance d-d_{eq} accounts for the case where a plume originates offshore and is subject to less atmospheric turbulence over water before coming onshore. The distance d is the actual distance the plume travels over the water, and d_{eq} is given as:

$$d_{eq} = \frac{s_{w,marine}}{s_{w,coastal}} d \qquad (2)$$

and represents an equivalent distance where the plume would be subjected to coastal rather than marine atmospheric conditions. The magnitude of the vertical wind fluctuation offshore is roughly half that of land, thus a good rule of thumb is to assume that the equivalent offshore distance, d_{eq}, is about half the actual distance, d. Note that the distance given by Equation (1) may be negative, in which case the distance from Table 1 would be reduced. However, this distance should not be reduced inside of a kilometer from the fire because of the unpredictable, transient nature of the near field environment that is not accounted for by the quasi-steady state model. This includes smoke traveling at low level due to smaller burning rates during fire ignition and extinction.

REFERENCES

1. Turner, J. S. *Buoyancy Effects in Fluids*. Cambridge University Press, Cambridge, England, 1973.

2. Turner, J. S. Proposed pragmatic methods for estimating plume rise and plume penetration through atmospheric layers. Atmospheric Environment, 19:1215-1218, 1985.

3. Wilson, R. B. Review of Development and Application of CRSTER and MPTER Models. Atmospheric Environment, 27B(1):41-57, 1993.

4. U.S. Environmental Protection Agency. User's Guide for the Industrial Source Complex (ISC3) Dispersion Models, Vol. II - Description and Model Algorithms, September 1995. Publication EPA-454/B-95-003b.

5. Perry, S. G. User's Guide to the Complex Terrain Dispersion Model Plus Algorithms for Unstable Situations (CTDMPLUS), Vol. I - Model Description and User's Instructions. U.S. Environmental Protection Agency, March 1989. National Technical Information Service Order No. PB89-181424.

6. DiCristogara, D. C. and S. R. Hanna. OCD: The Offshore and Coastal Dispersion Model, Volume 1: User's Guide. Sigma Research Corporation, Westford, Massachusetts, 1989. Report No. A085-1.

7. US Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina. A User's Guide for the CALPUFF Dispersion Model, July 1995. Publication EPA-454/B-95-006.

8. Briggs, G. A. *Plume Rise Predictions*, Lectures on Air Pollution and Environmental Impact Analysis. pp. 50-111. American Meteorology Society, Boston, 1975.

9. Baum, H. R., K. B. McGrattan, and R. G. Rehm. Simulation of Smoke Plumes from Large Pool Fires. In: *Proceedings of the 25th International Symposium on Combustion*, pp. 1463-1469. The Combustion Institute, Pittsburgh, Pennsylvania, August 1994.

10. McGrattan, K. B., H. R. Baum, and R. G. Rehm. Numerical Simulation of Smoke Plumes from Large Oil Fires. Atmospheric Environment, 30(24):4125-4136, 1996.

11. McGrattan, K. B., A. D. Putorti, W. H. Twilley, and D. D. Evans. Smoke Plume Trajectory of *In Situ* Burning of Crude Oil in Alaska. Technical Report NISTIR 5273, National Institute of Standards and Technology, Gaithersburg, Maryland, October 1993.

12. McGrattan, K. B., H. R. Baum, and R.G. Rehm. Smoke Plume Trajectory of *In Situ* Burning Of Crude Oil in Alaska. In: *Proceedings of the 17th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar,* pp. 725-734. Environment Canada, Emergencies Science Division, Ottawa, Ontario, Canada, June 1994.

13. McGrattan, K. B., W. D. Walton, A. D. Putorti, W. H. Twilley, J. McElroy, and D. D. Evans. Smoke Plume Trajectory of *In Situ* Burning of Crude Oil in Alaska - Field Experiments. In: *Proceedings of the 18th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*, pp. 901-914. Environment Canada, Emergencies Science Division, Ottawa, Ontario, Canada, June 1995.

14. McGrattan, K. B., H. R. Baum, W. D. Walton, and J. Trelles. Smoke Plume Trajectory of *In Situ* Burning of Crude Oil in Alaska—field experiments and modeling of complex terrain. Technical Report NISTIR 5958, National Institute of Standards and Technology, Gaithersburg, Maryland, January 1997.

15. EMCON Alaska, Inc., 4701 Business Park Boulevard, Suite 36, Anchorage, Alaska 99503-7166. Performance Evaluation of the ALOFT Model for Oil Spill Burns, September 1997. Project 55147-002.000 Task C2.

16. Walton, W. D. and K. B. McGrattan. ALOFT-FT™. National Institute of Standards and Technology, 1998. NIST SP 924, available via the Internet (http://fire.nist.gov).

17. Smolarkiewicz, P. K. and R. Rotunno. Low Froude Number Flow Past Three-Dimensional Obstacles. Part I: Baroclinically Generated Lee Vortices. Journal of the Atmospheric Sciences, 46:1154-1164, 1989.

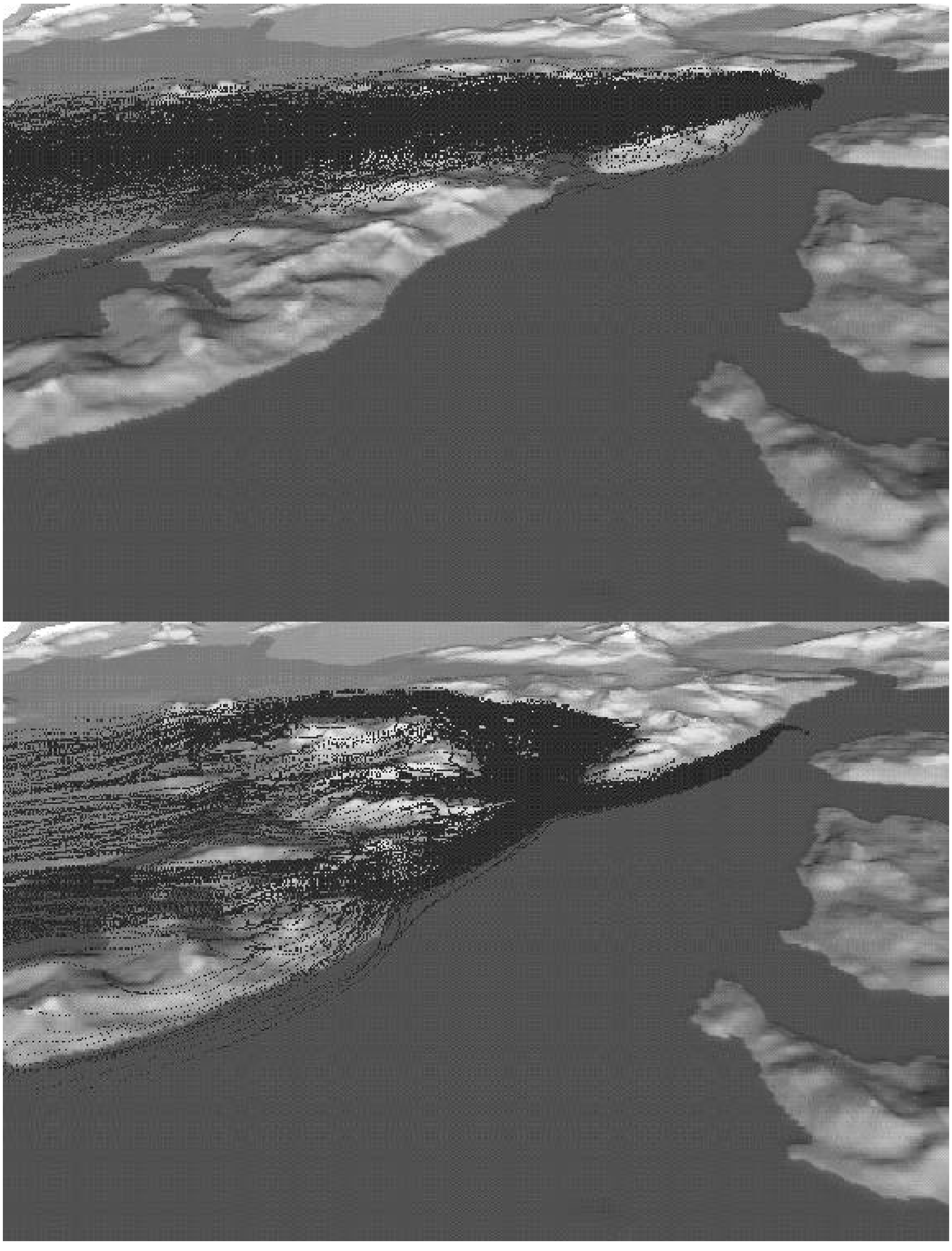

Figure 1. Three-dimensional views of smoke plumes originating in the Valdez Narrows, the entrance way to Port Valdez, Alaska. The top figure represents a case where the temperature of the

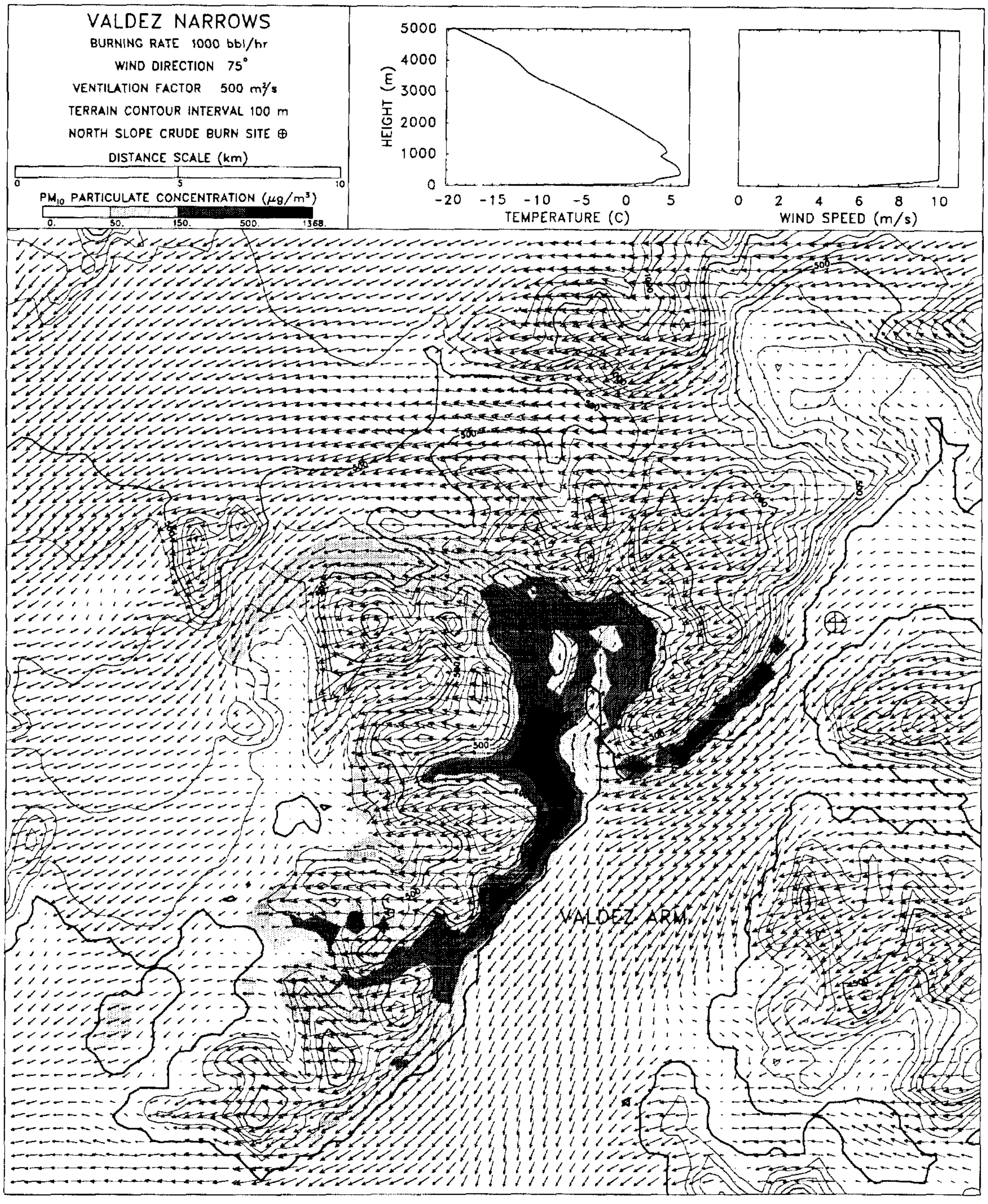

Figure 2. Ground level concentration of smoke particulate from a simulated smoke plume originating in the Valdez Narrows. This figure corresponds to the bottom picture in Figure 1.