SMOKE PLUME TRAJECTORY FROM IN SITU BURNING OF CRUDE OIL - FIELD EXPERIMENTS

by

K.B. McGrattan
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899
and
Ronald J. Ferek
Department of Atmospheric Sciences
University of Washington
Seattle, WA 98195
and
Edward E. Uthe
Geoscience and Engineering Center
SRI International
Menlo Park, CA 94025

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Kevin B. McGrattan
National Institute of Standards and Technology
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Ronald J. Ferek
Department of Atmospheric Sciences
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INTRODUCTION

There is growing interest in the environmental consequences of large fires, since the transport of combustion products by a windblown fire plume can distribute potentially hazardous materials over a wide area. Pools of burning oil and other petroleum products are of particular concern due to the vast flow of these materials through the global economy and because of the fragility of the environment in many regions where oil is extracted or transported. The present work is part of a larger study of a closely related issue, the feasibility of cleaning up oil spills on water through burning.

As part of the NIST program to study the burning properties of large pool fires, the Large Eddy Simulation (LES) model of smoke transport was developed to predict the concentration of combustion products downwind of a large fire [3]. The model consists of the conservation equations of mass, momentum and energy which describe the steady-state, convective transport of heated gases 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 which emanates from it. Only the heat release rate and smoke yield of the fuel are required from experiments. The local meteorological conditions which must be provided are the wind speed, the fluctuation in wind direction, and the temperature stratification of the atmosphere. The model has been applied in a number of studies to predict the downwind and lateral extent of ground level particulate concentrations in excess of established air quality standards [2].

Verification of this modeling effort with field measurements is extremely difficult due to the fact that the plumes are usually hundreds of meters high and the terrain is uncertain. *In situ* measurements at ground level, even if instruments are well placed, can often yield little or no data. In recent years, airborne measurements using a laser light scattering technique known as LIDAR has proven to be a very effective means to map an entire plume cross section, ultimately leading to estimates of smoke concentration over the entire slice. Two recent mesoscale burns have included LIDAR measurements, providing data with which to validate model simulations. The first test is the Newfoundland Offshore Burn Experiment (NOBE) conducted by Environment Canada in August 1993; the second, a series of mesoscale test burns held at the US Coast Guard Fire and Test Detachment, Mobile, Alabama in October 1994. The University of Washington Cloud and Aerosol Research Group performed the measurements in Newfoundland. Ed Uthe and Robert Kaiser from SRI performed the measurements in Mobile.

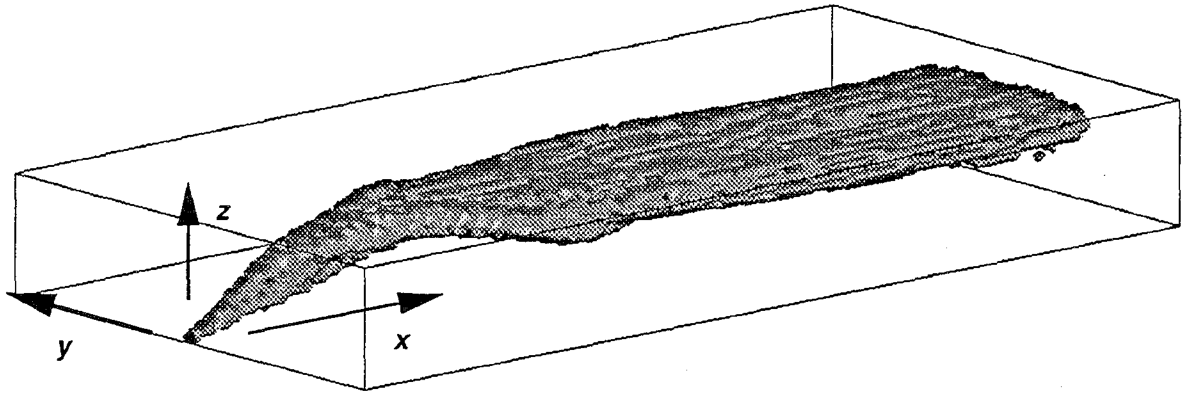

Figure 1: Three dimensional view of a computed smoke plume in the first few kilometers of its development. The height of the viewbox is 1 kilometer, the length 8 kilometers, and the crosswind length 4 km. The wind speed is 6 m/s. The computation is initialized by prescribing the temperature and particulate distribution in the plane spanned by the lateral and vertical coordinates. Then the plume is constructed as the smoke is swept downwind.

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. The experiment consisted of two *in situ* burns of crude oil conducted off the coast of St. John's, Newfoundland on August 12, 1993. Most of the measurements made involve properties of the fire itself rather than the downwind dispersion of particulate. However, the University of Washington scientists performed airborne measurements of the emission from the two *in situ* burns of crude oil. Of particular importance to the present study are the LIDAR measurements of the plume cross section. These measurements were made by flying above the plume and simultaneously transmitting laser pulses at two wavelengths (0.53 and 1.06 μm) while recording range-resolved backscattered energy from the atmosphere and reflected energy from the earth's surface. The final product of such measurements are cross-sectional images of the plume which can be quantified based on the properties of the particulate matter [6].

More data is available for the second burn, so that one will be used for the comparison. For this burn, it was reported that 28.9 m^3 of crude oil of density 843.7 kg/m^3 was burned in 1.3 hours [7]. For the purposes of modeling the plume, it was assumed that the burning rate was constant at 5.2 kg/s. Based on previous work with Louisiana crude [1], the effective heat of combustion of the oil was assumed to be 42,000 kJ/kg, even though a different oil was used for the tests. The smoke yield for the burn was measured by the team from NIST to be approximately 15% [4], and the fraction of the total heat release lost as radiation was assumed to be 10% [5]. Thus, the *convective* heat release rate for the model run was about 200 MW and the particulate production rate was 0.78 kg/s. Temperature soundings taken from the University of Washington aircraft and from the NIST tethered blimp [4] indicate that the temperature profile of the first few hundred meters of the atmosphere showed an inversion. The wind speed at the ground was about 5 to 6 m/s, increasing to about 8 m/s a few hundred meters up. This was accompanied by a shift of roughly 30 to 40° in the direction of the wind.

Fig. 2 displays cross sections of the simulated plume at downwind locations which approximately match those taken by the UofW team (See Fig. 3). 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[1] agreement between the two for a distance of about 6 kilometers from the fire. Beyond this point the simulation breaks down due to a lofting of the actual plume to a height of about 700 m. A LIDAR measurement taken along the plume centerline shows the plume initially rising to a height of about 200 m, leveling off for about 5 km, and then gradually rising 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. It is unclear exactly why it occurs. It has been speculated that this lofting might be due to the heat generated by the absorption of sunlight by the dark plume, the variable intensity of the fire, or the presence of local convective cells in the path of the plume. These details of the fire and the local meteorology cannot be well defined, pointing out the limitation of any predictive dispersion or meteorological model. Large scale patterns and trends can be predicted, but small scale details cannot.

MESOSCALE BURNS, MOBILE, ALABAMA

During October 1994, three mesoscale burns of diesel fuel were conducted at the US Coast Guard Fire and Safety Test Detachment in Mobile Bay. For each test about 17,000 liters of fuel were layed atop water in a 15.2 m square pan. The resulting smoke plume was observed with a two-wavelength (0.53 and 1.06 μm) airborne LIDAR plume and haze analyzer (ALPHA-2) flown on the SRI Queen Air in a vertically downward viewing direction. The aircraft followed a saw-toothed shaped path above the plume, taking measurements in slices perpendicular to the wind direction at various distances downwind of the fire. Backscatter signatures were processed for real-time height/distance color-modulated video displays that were used to help direct aircraft operations. The backscatter signatures along with aircraft location and time information were recorded on an optical disk for use in subsequent data analysis.

The three burns clearly demonstrated the importance of atmospheric conditions on establishing the downwind stucture of the plume and concentrations at surface level. During the first test, low winds allowed the plume to penetrate an elevated temperature inversion layer that resulted in convective cloud formation and a significant change in the plume direction due to the presence of a layer of wind shear. The next two burns were conducted under more stable atmospheric conditions, resulting in less plume penetration across the elevated inversion layer and more smoke closer to the surface far downwind. Presently, the data is being analyzed. Cross sections of the plume at various downwind distances will be presented, and the plume behavior discussed. In addition, mean particle size based on analysis of two-wavelength LIDAR backscatter and extinction measurements as a function of plume position will be presented.

[1]This quantification is based on an analysis of the scattering characteristics of the individual smoke particles. Details of the analysis may be found in Reference [6].

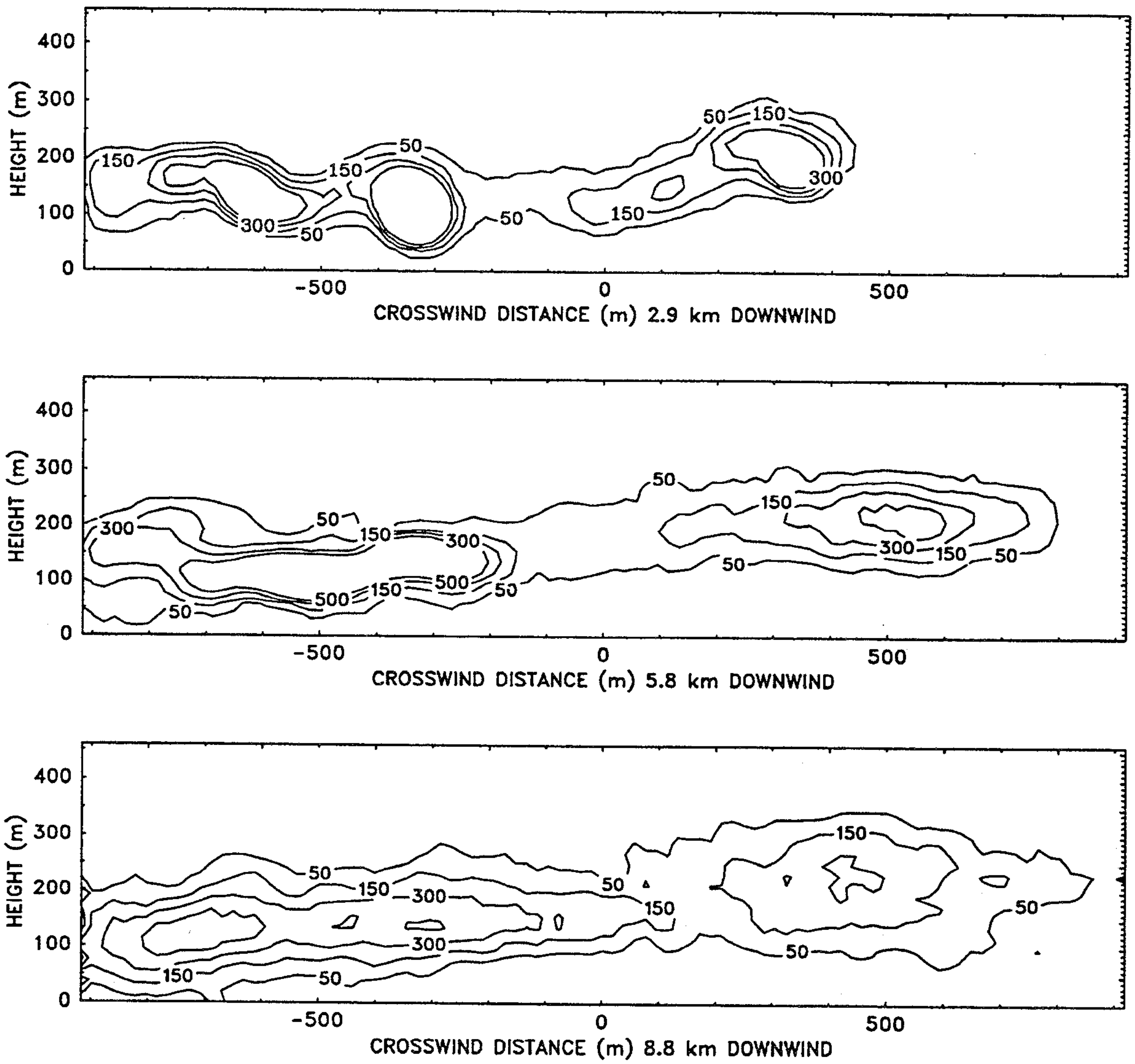

Figure 2: Cross sectional slices of the simulated smoke plume from the second NOBE burn. Shown are particulate concentration contours of 50, 150 and 300 $\mu g/m^3$ at three locations downwind corresponding to where LIDAR measurements were taken. The vertical length scale indicates height above sea level, while the horizontal scale indicates the distance from the assumed plume centerline.

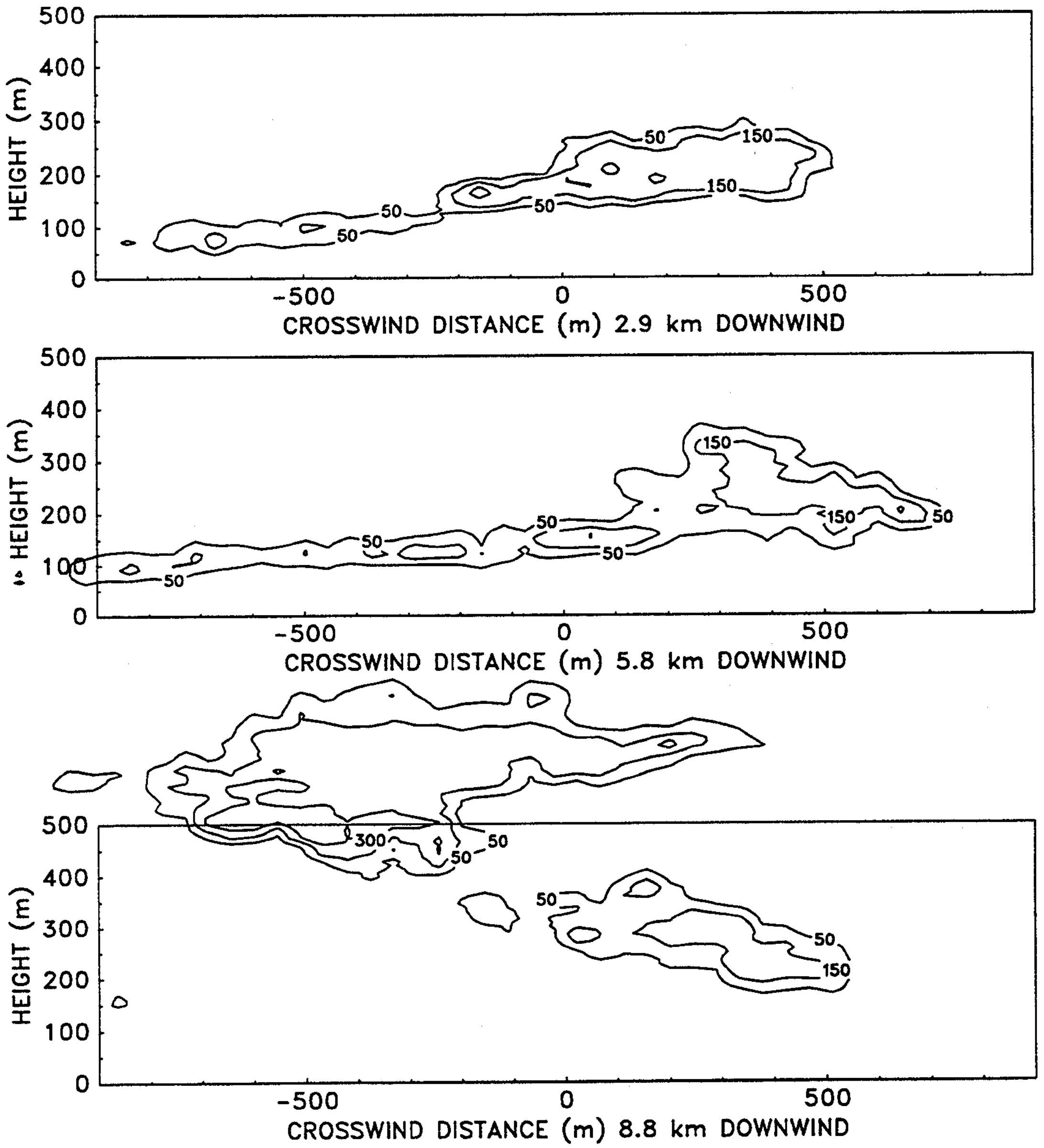

Figure 3: Cross sectional slices of the actual smoke plume from the second NOBE burn, courtesy of the University of Washington Cloud and Aerosol Research Group. Shown are contours of particulate concentration at 50, 150 and 300 $\mu g/m^3$. The crosswind scale indicates relative distances, and the origin was chosen to compare with the simulation.

ACKNOWLEDGEMENTS

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