HYDROCODE STUDIES OF FLOWS GENERATED BY LARGE AREA FIRES

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ABSTRACT

The global computational approach to the simulation of the meso-scale motions generated by a large area fire is described. Existing hydrocode solutions are reviewed and ongoing calculations discussed. Assumptions applied in many hydrocode solutions are assessed, and modeling requirements based on recent analytical efforts are defined.

INTRODUCTION

The flow system generated by a large area fire is characterized by a high-speed radial inflow near the ground and a very large free-convection column. For fires as large or larger than the World War II firestorms (1, 2), the low-level inflows are expected to be of hurricane force, and the convection columns are expected to ascend through much of the atmosphere. Perturbations of such magnitude should additionally induce significant meso-scale motions outside the column. Such motions might, for example, be vortex-like and pump air in towards the fire, increasing the fire-wind inflow (3, 4).

This paper reviews the large hydrocode approach to the simultaneous simulation of all components (inflow, column upflow, far field) of the fire-generated flow system. The complexities inherent in adopting this approach are discussed, and progress made to date is summarized. The alternative analytical approach is to consider individual flow components separately and match them together in a suitable manner (3). Although significant results concerning the near-fire inflow have been developed (5) and modifications of standard plume theory may (or may not (3)) provide a suitable description of the weakly-buoyant column flow, no component analysis of the far field has yet been completed. Such an analysis may of necessity be computational and involve hydrocode usage.

HYDROCODE ANALYSIS

Conceptually, the full Navier-Stokes, energy, continuity, species, and combustion equations (6) can be solved numerically and the fire-generated flow field defined in an infinite domain. For many problems of interest, current models of the burning processes, flow chemistry, and turbulent structure do not justify such a rigorous modeling. Accordingly, a number of simplifying assumptions have been used (4, 7-10). They include an isothermal boundary condition to model the heat release by combustion (7 - 9), the Boussinesq approximation (7 - 10), either a constant eddy diffusivity (4, 7 - 9) or k-ε model (10) to describe the turbulent structure and a finite-volume heat source (4).

With the heat addition modeled by an isothermal condition at the ground, the production of buoyancy depends on the diffusion of energy from the boundary. Coupled with the Boussinesq approximation, use of an isothermal condition

restricts the solution to weakly buoyant motions similar in principle to flows generated by urban heat islands (11, 12). Such motions tend to form very thin columns, unlike actual fire systems in which the highly-turbulent, strongly-buoyant near-fire flow produces a column whose width is comparable to that of the fuel bed (13). In order to adequately simulate the qualitative aspects of large-fire flows, hydrocode models must therefore treat the near-fire (or source) region with some care.

A fine zoning of the source region is of course a necessity. Beyond that, the use of a finite-volume heat source is recommended, and more accurate turbulence modeling may be considered. Recent studies (14) of the source-region flow component indicate that it depends strongly on the height of the heating region (see Fig. 1), but is relatively insensitive to the spatial distribution of the heat release. The use of a finite-volume heat release should thus not be restricted by a limited data base, but should greatly improve the modeling. The level of turbulence in the source region should be greater than that in the slower-moving, overhead column, and much greater than outside the column. An adequate definition of the source-region turbulence is at present lacking, however, and current models are correspondingly crude. The current radiation models are simple graybody losses, which are also quite approximate. Radiation should play a negligible role over most of the flow field, but is expected to be of importance in the early (low-level) decay of the high-temperature source flow to the weakly-buoyant column flow.

Current hydrocode solutions all show large fire-wind inflows near the source region. Smith, Morton and Leslie (8) relate the induced fire winds to the dynamic pressure field generated by the buoyancy. The pressure gradients are greatest in the neighborhood of the fire zone and decay rapidly with distance from the fire perimeter. The generation of a high-velocity inflow near the fire by pressure gradients rather than by viscous entrainment is consistent with the observations of Cox and Chitty (15).

An interesting feature of several large-scale solutions has been the development of well-defined vortex structures. Delage and Taylor (12) describe early-time roll motions above an urban heat island as well as the development of a meso-scale recirculation (cf. 3, 11). Luti and Brzustowski (9) examine the generation of lee-side vortices by a heat source in cross flow.

Larson, Brode, and Small (4) consider the strongly buoyant flow produced by area fire of 10 km radius, and describe the time history of several vortex motions. The volume heat addition generates several rotating cells in the source region (Fig. 2). The continued, constant production of buoyancy generates a strengthening inflow that gradually imposes a radially directed flow in the source region (Fig. 3). As the inflow strengthens, a strong vortex develops above the fire perimeter (Fig. 4) and is eventually shed. The outward motion of that vortex produces a stronger inflow that extends approximately one fire radius beyond the fire boundary. As the vortex moves to infinity, the inflow weakens and roll motions reappear in the burning region. The cycle repeats at approximately 20 minute intervals in this particular case. In related, ongoing hydrocode studies, similar results are being obtained (16).

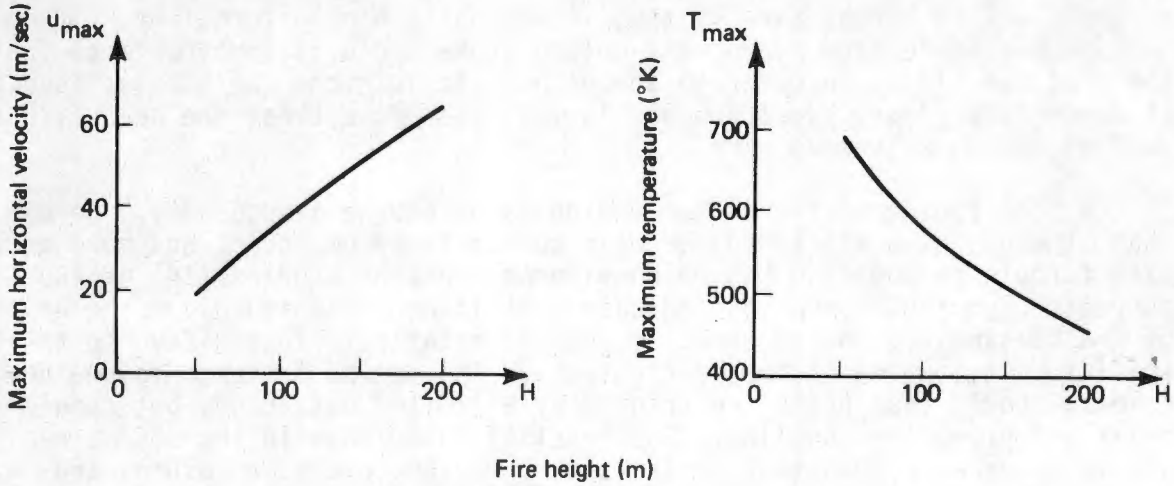

Fig. 1. Dependence of maximum radial velocity and temperature on fire height.

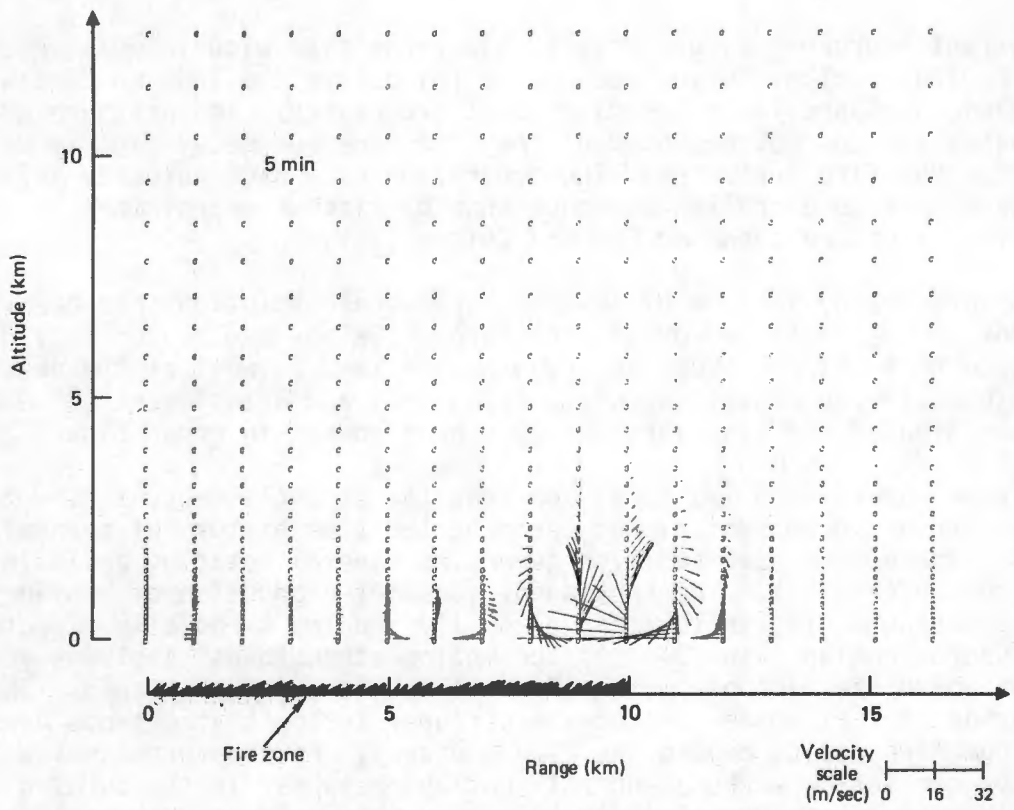

Fig. 2. Simulated flow field at 5 min. after ignition for sample 10 km fire.

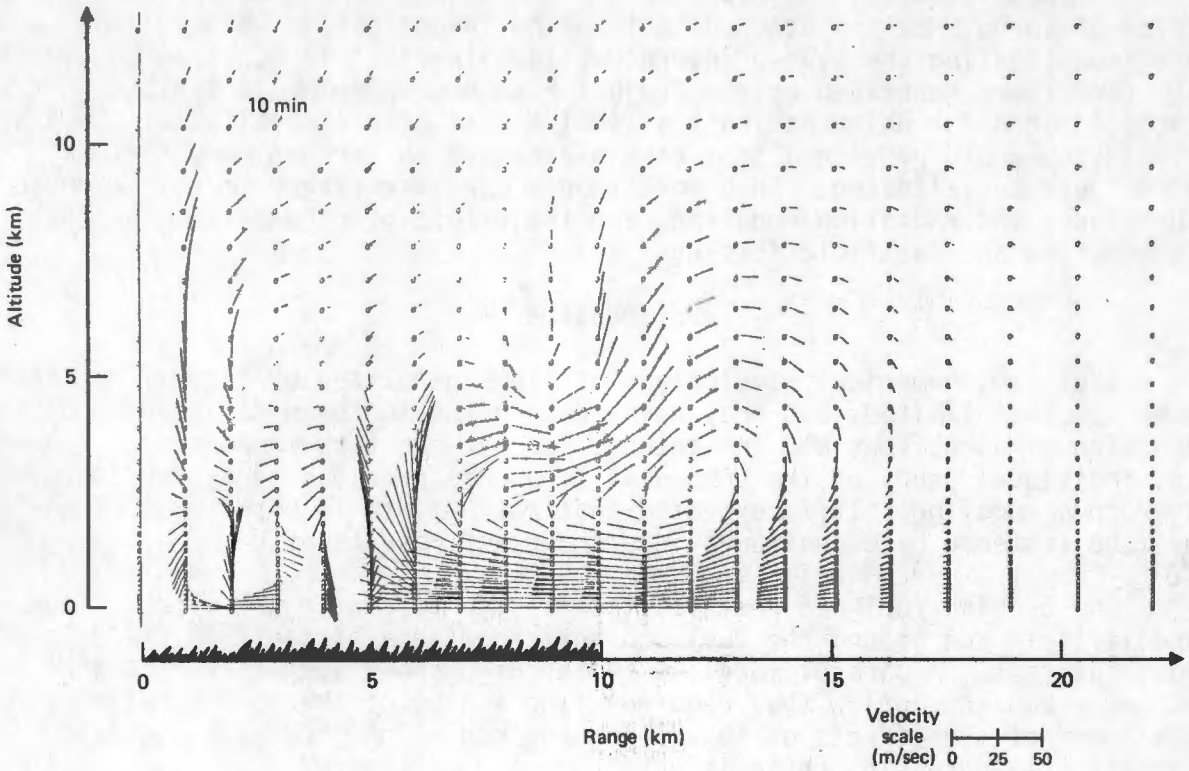

Fig. 3. Simulated flow field at 10 min. for sample 10 km fire.

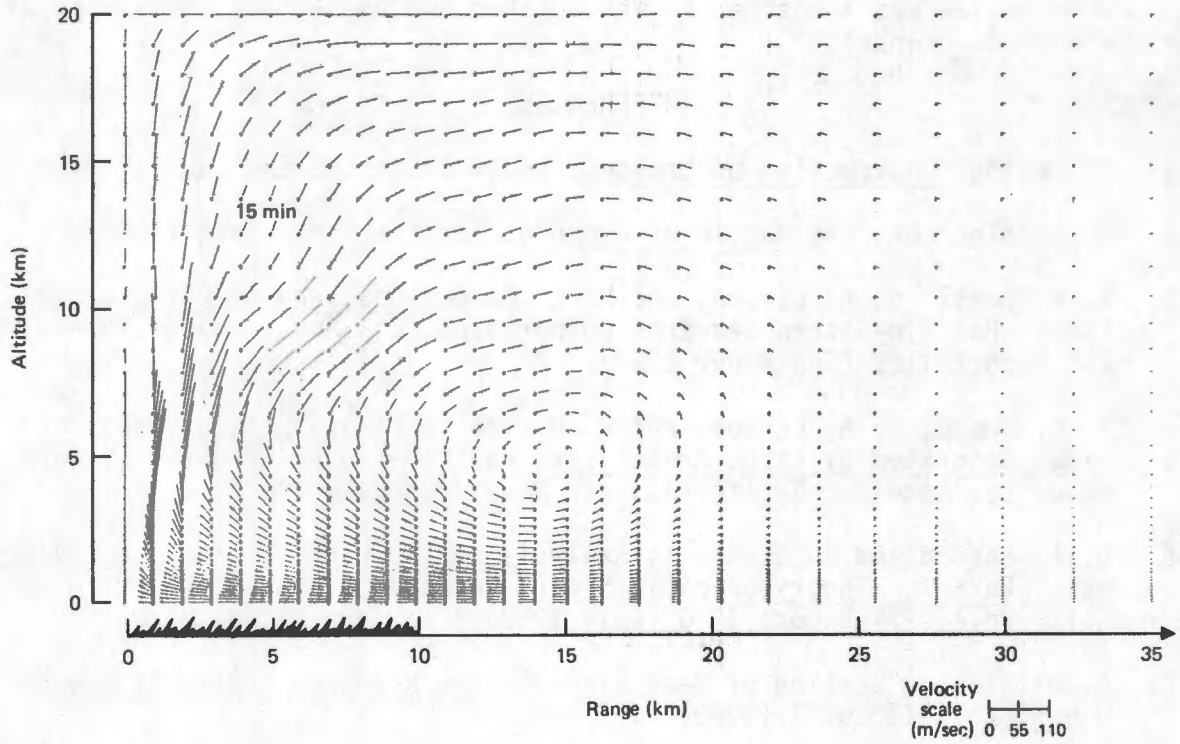

Fig. 4. Simulated flow field at 15 min for sample 10 km fire.

In those studies, the dependence of solutions on boundary conditions, level of turbulence and other data is being investigated. In addition, we are investigating the type of hydrocode modeling that is required to simulate the fire flows generated by the Project Flambeau experiments (13), the largest fires for which at least a limited data base is available. Such a simulation would provide a test case against which further computational work could be validated. Such work should consider larger fires, improved turbulence and radiation modeling, and the effect of condensation on the column flow and far-field forcing.

DISCUSSION

Thus far, numerical simulations of flows generated by large fires have been somewhat limited, but they have contributed to the understanding of the dynamics of such flows and the interaction between flow components. Conversely, individual study of the component flows has provided ideas for improved hydrocode modeling. It is expected that refinements in both types of analysis will be fostered by a continued interchange of results.

The burning fuel bed provides the driving force for the overall flow, and it is in and around the fuel bed that knowledge of the flow field is of most interest. A careful modeling of the high-speed surface inflow and strongly buoyant upflow thus requires fine zoning of the source region and treatment of the effects of turbulence and radiation. Current modeling efforts are addressing those issues.

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REFERENCES

1. D. Irving, Destruction of Dresden, Kimber, London, England (1963).

2. M. Middlebrook, The Battle of Hamburg, Scribner, New York (1981).

3. R. D. Small, D. A. Larson, and H. L. Brode, Analysis of Large Urban Fires, Pacific-Sierra Research Corporation, Los Angeles, California, PSR Report 1122 (September 1981).

4. H. L. Brode, D. A. Larson, and R. D. Small, Time-Dependent Model of Flows Generated by Large Area Fires, Pacific-Sierra Research Corporation, Los Angeles, California, PSR Note 482 (July 1982).

5. D. A. Larson and R. D. Small, Analysis of the Large Urban Fire Environment, Part I: Theory, Pacific-Sierra Research Corporation, Los Angeles, California, PSR Report 1210 (July 1982).

6. F. Williams, "Scaling of Mass Fires," Fire Research Abstracts and Reviews, Vol. 11, p. 1 (1969).

7. H. J. Nielsen, Mass Fire Data Analysis, ITT Research Institute, Chicago, Illinois, DASA Report No. 2018 (January 1970).

8. R. K. Smith, B. R. Morton, and L. M. Leslie, "The Role of Dynamic Pressure in Generating Fire Winds," Journal of Fluid Mechanics, Vol. 68, pp. 1-19 (1975).

9. F. M. Luti and T. A. Brzustowski, "Flow Due to a Two-Dimensional Heat Source with Cross Flow in the Atmosphere," Combustion Science and Technology, Vol. 16, pp. 71-87 (1977).

10. F. M. Luti and T. A. Brzustowski, "Some Characteristics of a Two-Dimensional Starting Mass Fire with Cross Flow," Combustion Science and Technology, Vol. 26, pp. 25-33 (1981).

11. M. A. Estoque and C. M. Bhumralkar, "Flow Over a Localized Heat Source," Monthly Weather Review, Vol. 97, pp. 850-859 (1969).

12. Y. Delage and P. A. Taylor, "Numerical Studies of Heat Island Circulation," Boundary Layer Meteorology, Vol. 1, pp. 201-226 (1970).

13. C. M. Countryman, PROJECT FLAMBEAU...An Investigation of Mass Fire (1964-1967), Vol. 1, U.S. Forest Service, Berkeley, California (1969).

14. D. A. Larson and R. D. Small, Analysis of the Large Urban Fire Environment, Part II: Parametric Analysis and Model City Simulations, Pacific-Sierra Research Corporation, Los Angeles, California, PSR Report 1210 (November 1982).

15. G. Cox and R. Chitty, "A Study of the Deterministic Properties of Unbounded Fire Plumes," Combustion and Flame, Vol 39, pp. 191-199 (1980).

16. M. Rossenblatt, P. Hassig, and D. Kanne, private communication (March 1983).