High resolution, near field, meteorological wind analysis system for emergency response and other applications

R.M. Cionco, J.H. Byers

U.S. Army Research Laboratory, ATTN:AMSRL-BE-S, White Sands Missile Range, New Mexico 88002-5501, USA

Abstract

In most emergency response activities, it is essential to know how the local meteorological conditions and terrain can affect inadvertent and accidental releases and other operations. A better representation of the near field meteorology will ensure a more accurate and dependable on-site handling of situations of hazardous materials. This means including the presence and effects of land feature morphology (i.e. vegetation, buildings, etc) as well as terrain in your analysis. To transform meteorological models/codes into information for response and assessment during emergency activities, some seven tasks may be implemented with a high resolution, micrometeorological code in-hand. The user can then analyze areas affected as having adverse and favorable impacts at and downwind of the hazardous release site. The results of the effects analysis can be interpreted on-site for customized use and assessment information. This wind simulation and effects analysis system was used successfully during the planning stages and on-site, real-time during the conduct of the recent MADONA Field Study. The described methods can easily be adapted to a variety of other field activities where the wind is influenced by the presence and configuration of variable terrain, and building and vegetation features within the domain.

1. Introduction

A high resolution meteorological simulation and analysis system of codes implemented on a high performance lap top was tested during a recent field study in a situation similar to an emergency response-type operation. The high resolution wind model and its complimentary effects (impact) analysis method, called HRW, 1.1, was run real-time using on-site, real-time
meteorological measurements to initialize the wind code as both smoke and SF$_6$ plumes and puffs were released within a very localized area. The purpose of this field study, called MADONA$^2$, was to collect meteorological and aerosol concentration data required to test and evaluate our library of models.

With the simulation and analysis system installed on our lap top along with the digitized terrain elevation and land feature morphology data, we responded to the release of smoke and tracer materials by preparing model initialization input data from on-site, real-time meteorological data and then simulated the high resolution, mean quantity wind and temperature fields for the near field domain of the field study. Doing each of the simulation and analysis tasks real-time while the source created a continuous plumes and instantaneous puffs, in essence was emulating the meteorological activities and components for an emergency response scenario (obviously without the usual expediency and confusion of the real event). The same approach can be applied also to similar sets of field activities and operations when aerosol are released into the atmosphere and their downwind behavior must be quantified and analyzed for their control or the protection of a community in the near field domain.

Other types of field activities and operations that can be addressed with these methods are: the behavior of aerial-released aerosols and drift analysis of pesticide spray; the management of smoke produced during forest service slash and burn operations; the behavioral studies of the release and travel of spores and disease in agricultural and forested areas; the general release of aerosol that must be quantified, analyzed, and monitored for control, health, and safety, and similar other operations.

Note that near field in this concept refers to areas of the order of 5Km by 5Km with the source located within these boundaries. High resolution equates to a computational grid of 100m in x and y for the 5Km by 5Km area, but may also range from 40m to 400m as the domain size changes from 2Km by 2Km to 20Km by 20Km.

2. Discussion

To transform meteorological model/code output into information for response and assessment during emergency and the above mentioned activities, the following tasks may be satisfied with a high resolution micrometeorological wind flow model/code in-hand appropriate for emergency response: (1) identify digitized terrain data sets and digitized land feature morphology data sets (optional); (2) identify source of meteorological input data (fixed installation, safari, or central office); (3) simulate high resolution wind fields for emergency events; (4) analyze terrain, land feature, and thermal effects upon the wind and other meteorological variables; (5) use criteria appropriate for the "operational or hazardous" event to classify and further identify areas.
of concern/impact about the hazardous release; (6) visualize, interpret and depict the meteorological fields and effects analyses; (7) analyze areas of effect for adverse and favorable impacts at and downwind of the hazardous release site. The user can then interpret the results of the effects analysis on-site for customized use and assessment information.

This method can easily be adapted to a variety of emergency response situations where the wind is influenced by terrain and land feature morphology. It also can be a useful simulation tool in preparedness planning, training, and later for post-analysis. This wind simulation and effects analysis method\(^1\) was used successfully during the planning stages and again in the conduct of the MADONA Field Study\(^2\). With the digitized terrain/land feature data installed in the lap top, on-site field observations were transformed real-time into code inputs for high-resolution wind field simulations.

3. Model and method

Two microscale models can be considered for this high resolution analysis of flow over complex terrain and optional within and above land use features. The first code, HRW\(^3\), analyzes horizontal wind and temperature fields over a local area of some 5 km by 5 km. The second code, C-CSL\(^3\), couples the same HRW surface layer flow with canopy flow for a similar domain. This meteorological coupling adds vertical structure to the simulated horizontal wind field. For the general purpose being addressed here, the HRW code is chosen to provide the simulated meteorological fields for the effects/impact analysis described herein because it addresses a high-resolution, small domain for near field analyses with minimum inputs and because it is also fast, friendly, and easy to implement and view results.

3.1 The high resolution wind model

The HRW model is a two-dimensional, diagnostic, time independent model that simulates the wind flow over a grided area of 5 km by 5 km with a nominal spacial resolution of 100 meters. The code is initialized with single values of time-averaged surface layer wind speed, wind direction, temperature, and an estimate of buoyancy by applying these values at each grid point in the computational array. Simulation results are obtained by a direct variational relaxation of the wind and temperature fields in the surface layer. The solution is reached when the internal constraint forces imposed by the warped terrain surface, thermal structure and requirement for flow continuity are minimized. The procedure makes use of Gauss’ Principle of Least Constraints \(^4\) which requires these forces to be minimized in order to satisfy the equations of motion. When applied to the surface layer, this procedure also requires the use of empirical wind and temperature profiles. As mentioned earlier, the computational domain size can range from 2 km by
2 km to 20 km with grid resolutions varying from 40 meters to 400 meters respectively. The vertical thickness of the computational layer is designed to be 1/10th the magnitude of the grid size. A grid size of 100 m therefore produces simulated fields at the 10 m level as a result of integrating through the thickness of this layer.

The initialization of the wind code requires surface layer values of wind speed, wind direction, and temperature at one location at the 10 m level in addition to an upper air temperature-pressure-height profile to estimate the surface domain’s bulk buoyancy. Terrain elevation data and land use feature information in a digital format are also required. For output, the following simulated x,y fields are computed at the top of the 10 m layer: (a) u and v wind components, (b) potential temperature, (c) friction velocity, (d) wind power law exponent, and (e) the Richardson Number. The vertical wind profile also can be calculated at each grid point through the computational layer. Note that all simulated values represent a five minute average and are also valid for a period of up to one hour for this microscale surface layer domain.

An example showing a comparison of a simulated horizontal mean wind field and the concurrent observed field of 14 sites is shown in Figure 1 for a computational grid of 100 m in x and y. A streamline analysis of the simulated vector field is presented rather than the vector field. The agreement is quite reasonable, however, the reader must be advised that although the direction agreement is in-scale, the observed speed vectors are not to the same scale as the simulated field.

### 3.2 The effects/impact method

The effects/impact analysis method is developed to identify and quantify the degree and character of the effect (impact) of wind, terrain, and land use features upon a field event or operation. The concept of 'impact' refers to the resultant effect of the wind speed increasing or decreasing notably or the wind changing direction significantly from the initialization field somewhere in the domain because of direct interaction with the changing terrain and land use features and thermal buoyancy. The method does this by applying operational criteria to the resultant effect of the simulated field versus the initial field from the HRW code. During the MADONA field study, criteria were established specifically in regard to the release site of smoke and SF₆ aerosol and the downwind travel area of the plumes and puffs for a reasonable measurements setup of concentration amounts.

The method involves analyzing the newly simulated field in comparison to the initialized field:

\[
\text{EFFECT} = \text{FINAL SIMULATED FIELD} - \text{INITIAL FIELD}
\]
More specifically, the wind speed effect and the wind direction effect are determined separately. The Wind speed Effect ($E_{ws}$) is the difference between the values for the final simulated wind speed field ($S_g$) and the initial wind speed field ($S_i$):

$$E_{ws} = S_g - S_i$$ (1)

The Wind Direction Effect ($E_{wd}$) is the difference between the values for the final simulated wind direction field ($D_g$) and the initial wind direction field ($D_i$):

$$E_{wd} = D_g - D_i$$ (2)

A qualitative assessment of the Total Effect can be made next combining the effects of the two difference fields. To quantify these effects, a set of appropriate operational criteria is established for the emergency or similar type of activities. By example, three levels of Effect are defined for MADONA diffusion experiments:

LIGHT if:

$$E_{ws} < 10\% \ of \ S_i, \ \ and \ \ E_{wd} < 10^\circ \ of \ D_i$$ (3)

MODERATE if:

$$E_{ws} \ is \ 10\% \ to \ 50\% \ of \ S_i, \ \ and \ \ E_{wd} \ is \ 10^\circ \ to \ 30^\circ \ of \ D_i$$ (4)

SEVERE if:

$$E_{ws} > 50\% \ of \ S_i, \ \ and \ \ E_{wd} > 30^\circ \ of \ D_i$$ (5)

The visualization scheme is next implemented to overlay a color coded map of areas of these three impact levels onto plots of the terrain and land feature morphology and wind streamlines. It should be noted that you, the user, set the "operational" criteria and the visualization technique to fit your specific requirements be they emergency response or otherwise.

4. Results

To illustrate the impact (effects) analysis technique, several simulations made during the MADONA field study are selected to represent examples of two levels of impact. Examples of light-to-moderate and severe impact cases are presented to demonstrate where it was feasible to release and measure the aerosol plumes and puffs.
Light-to-moderate impact areas are shown in Figure 2 initialized with a mean wind of 3.0 m/s from the west at 250 degrees which nearly parallel the terrain features causing a light to moderate effect of terrain upon the meteorology. The plot for the impact analysis of this case indicates that a wide area of light wind effects (white areas without symbols) has opened up in the area of the Bowl where the aerosol generators were located. Moderate impact areas (gray and hatched areas) are observed immediately to the south of the Bowl, along the ridge and hill tops. Several small areas of severe impact (black and cross-hatched areas) are indicated at the highest elevations. The interpretation is that in the more uniform, lower elevation of the Bowl, the plumes would behave as expected and measurement systems (lidars) could be located with confidence. The tracer plume would not be accelerating or decelerating notably (<10%) to cause dilution, pooling, or accumulation. Nor would it change direction (<10°) significantly and therefore cause possible endangerment to unexpected areas. In the limited moderate and severe areas of this simulation, the plume behavior would sufficiently change travel in both speed and direction to produce areas of greater effect or adverse impact. These more notable changes could define where adverse conditions such as pooling and stagnation are and also alert the emergency team where vulnerable locations may be.

A severe impact case is shown in Figure 3. This simulation indicates severe adverse wind effects in large areas throughout the entire domain. The initial mean wind speed and wind direction for this simulation was 1.0 m/s and 180 degrees. As would be expected for these light speed conditions, the streamline plot indicates meandering winds, twisting and turning and flowing from the south. Although an attempt to release "puffs" was made, the tests were aborted because a dependable wind speed and direction could not be maintained for a reasonable time period. The field notes show this to be a no test day. The simulation verifies this to be a correct decision. The adverse impact plot indicates virtually no contiguous area large enough that would be suitable for a valid test. In the case of inadvertent and accidental releases, the entire area could be vulnerable to serious problems because of the high degree of occurrence of acceleration, deceleration, and highly variable directional changes. Once the source is located, one can then consider a more limited area of travel and, therefore, the potential behavior of the ‘dispersion’ of the aerosol plume.

5. Conclusion

It is shown for activities of an emergency nature as well as other applications that the near field situation can be simulated and analyzed in an efficient and highly representative way given appropriate, customized operational criteria. The field testing of HRW and its complimentary impact analysis method was
successfully accomplished in real-time during a recent set of meteorological and diffusion field trials. The implementation of this simulation and analysis approach onto a high performance lap top allows you to make a quick assessment on-site and real-time of the impact of the wind and terrain/land use features effect upon your emergency response activity. As shown by the above simulations, solutions, and analyses, the wind simulation and impact technique can be a useful tool for on-site use. The system can work equally as good for support of other activities that are notably influenced by their interactions with wind and terrain effects. Activities such as the management of smoke released during forest service slash and burn operations, the aerial release and drift analysis during pesticide spray operations, studies of the transport of spores and disease over forested and agricultural areas, the general diffusion of aerosols for areas of pooling, accumulation, dilution, and higher concentration and dosage locations specifically for the near field and other similar applications.

References


Figure 1. Comparison of simulated field with observations.
Figure 2. Example of LIGHT TO MODERATE impact. Streamlines/Adverse Impact areas. Julian Day: 262
Time: 1449  Direction: 250 Deg.  Speed: 3.0 m/s.
Figure 3. Example of SEVERE impact. Streamlines/Adverse Impact areas. Julian Day: 261
Time: 1415 Direction: 180 Deg. Speed: 1.0 m/s.