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**Prototype of a Coupled Mesoscale-Microscale
Modeling System**

by Saba A. Luces and Ronald M. Cionco

ARL-TR-3706

January 2006

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Prototype of a Coupled Mesoscale-Microscale Modeling System

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Computational and Information Sciences Directorate

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Summary

In order to address the lack of low-level forecast wind response to true high-resolution terrain in the Battlescale Forecast Model (BFM), the U.S. Army Research Laboratory (ARL) has developed a prototype system of coupled mesoscale and microscale models that considers higher-resolution terrain in its analysis. Research was initiated to integrate the microscale High-Resolution Wind (HRW) model code (which has long been used to perform diagnostic studies of the effects of terrain and vegetation on local winds) with the mesoscale BFM code to attain higher-resolution meteorological forecasts for target areas and other localized areas on the battlefield. A step-wise approach was employed to develop a modular prototype that would first show improved winds using high-resolution diagnostic models, but then be capable of interchanging various components. The San Francisco Bay, CA, area was selected as the common simulation domain, since both the BFM and the HRW had been run there in previous studies.

To begin, model output was gathered and model input datasets were generated for the initialization of both models. Next, the codes were run as separate entities to evaluate model output and input compatibilities for several cases. Later, the HRW was incorporated into the Artillery BFM run, but with a separate execution for each target area. Level 1 Digital Terrain Elevation Data (DTED) were already in hand for the HRW and BFM at the desired resolutions, and meteorological input data for the BFM were obtained from the Navy Operational Global Atmospheric Prediction System (NOGAPS) at a 1° resolution. Initially, meteorological input data for the HRW were generated from the BFM simulations in the form of an equivalent upper-air sounding and 10-m meteorological surface station observation, derived from a single BFM grid point with its vertical extension “centered” on the HRW domain. Subsequently, surface data from the surrounding BFM grid points were added to the HRW run and later formed into an objective analysis.

The new mesoscale-microscale (BFM-HRW) simulations compared well against the solutions previously run for the San Francisco, CA, area. More recently, additional runs have been performed at other locations with other forecast and diagnostic models. These modifications will be presented in a subsequent report.

1. Introduction

The U.S. Army Research Laboratory (ARL) has long used a microscale High-Resolution Wind (HRW) model (Cionco, 1985) to perform diagnostic studies of the effects of terrain and vegetation on local winds. ARL has also used a hydrostatic mesoscale forecast model, the Battlescale Forecast Model (BFM) (Henmi and Dumais, 1998), to produce tailored forecast products. Studies of the effectiveness of the BFM to produce low-level target area forecast products in complex terrain have demonstrated that low-level mesoscale forecast winds are unable to respond to the true high-resolution terrain (Henmi, 2000).

As a consequence, a prototype system of coupled mesoscale and microscale models has been conceived to produce an analysis that considers higher-resolution terrain. Research was initiated to integrate the HRW with the BFM to attain higher-resolution meteorological forecasts for target areas and other localized areas on the battlefield. Projected changes in forecast model and projected three-dimensional requirements for the diagnostic model dictated that the prototype be developed with modularity.

Thus, the resultant prototype system, which consists of interchangeable models, can be applied to other military problems, such as the highly important issue of the transport and diffusion of chemical and biological materials on the battlefield. The mesoscale-microscale model output can provide data showing coarse- and fine-scale winds influenced by detailed surface features (such as vegetation or structures), as well as the underlying complex terrain. The scope of this report, however, will be restricted to how the models being integrated relate to the field artillery problem and its target area.

2. Objective

The objectives of the study are to develop a prototype modeling system to accomplish the following:

1. Attain higher-resolution surface layer meteorological (Met) analyses than are available from existing mesoscale analyses for the target area and other battlefield areas of interest.
2. Use the ARL HRW model to attain higher computational resolution at forecast hours.
3. Complete a transfer technology from basic research to an applied research project.
4. Retain the capability to change parts of the prototype to cope with changing requirements and the evolution of the ARL models.

This report details examples of the first steps towards developing a prototype (BFM-HRW simulations) and contrasts the results of the BFM alone versus the prototype of coupled models.

3. Approach

Rather than attempt to build the code for high-resolution modeling into the mesoscale model, a more modular, and definitely easier, method was chosen. This simple method utilizes intermediate code to capture the proper location within the mesoscale model output and then writes out the required data in the format required as input to the microscale model.

A step-wise approach was used to attain coupling and integration of the models. As a first test of the process, the method was applied to our support of the Department of Defense (DoD)–Massachusetts Institute of Technology (MIT)–Lincoln Lab Smart Sensor Webs Project for the Weather Web (WXWEB) demonstration at the Military Operations on Urbanized Terrain (MOU) site at Ft. Benning, GA, during August 2000. During this test, we selected the Met message gun and target locations in the mesoscale Computer Aided Artillery Meteorology (CAAM) program (the prototype software for the now fielded Meteorological Sensor System-Profiler (MSS-P) system) as the center of the MOU site, printed the Met message values at that location, and then manually entered this data into the required microscale model input file.

In the next test, a simulation domain common to both the mesoscale and microscale models was identified, so that prior runs of the microscale model could be compared to new runs with the models coupled. The domain for the selected mesoscale model, the Artillery version of the BFM (Haines et al., 1997), was set up to match the high-resolution target area of previous runs of a domain for the microscale model, the HRW. The location selected was the San Francisco Bay, CA, area. HRW input files derived from BFM output were manually generated for the same days as prior HRW runs. The new and old HRW runs were compared for consistency. Qualitatively, the solutions were considered to be consistent with each other. To provide a finer analysis, the BFM computational grid was adjusted from 5 km to 2.5 km. Model output comparisons proved to be compatible and consistent in the manual mode.

To begin the integration process, the CAAM program was set up to output the required input file for the microscale code at the point in its execution when it was forming the target-area low-level Met message. Model results were again compared with similar success. The microscale input was changed to accept a terrain file similar to that of the mesoscale input. Microscale output was also changed to resemble the mesoscale output file, so that its visualization could be made easier. The setup of the Artillery program was altered to form microscale terrain files every time a target area was selected. Finally, the operation of the Artillery program was set to run the microscale code every time a Met message was required. The microscale output for the lowest level of the message line was retrieved for the Met message.

For this study, several changes and accommodations were made to model input and output, either by choice or by dictation from the coupling and integrating process.

For model input, the following conditions were implemented:

1. The input file derived from the mesoscale code consists of a single “upper air” profile of potential temperature versus height for mandatory levels (850, 700, and 500 mbar); however, the mesoscale model surface station Met output was provided as 16 adjacent

mesoscale grids rather than 1 surface station input. These 16 data points were analyzed using a Barnes analysis, and slope flow wind calculations were derived from software in the Earth Tech Inc. diagnostic Met model called CALMET (Scire et al., 2000).

2. Digitized terrain elevation was provided from the mesoscale terrain cache originally extracted from Digital Terrain Elevation Data (DTED) Level-1 CD-ROMs.
3. Land feature morphology data was not available at the required resolution; therefore, only surface roughness was used.

For model output, the following conditions were followed:

- Binary files of wind components, temperature, and the Power-Law Exponent were separated and used for Artillery Met messages and display.
- The microscale output was made to be similar to the mesoscale output file so we could adapt that translation software for visualization of the BFM in the University of Wisconsin's Space Science and Engineering Center tool for visualizing five-dimensional data, VIS5D (Hibbard et al., 1998).
- The microscale variables displayed with VIS5D were wind vectors, streamlines, temperature, and terrain elevation.
- For the Artillery Met message, the Power-Law Exponent was used to build a wind profile to blend microscale surface wind to an interpolated mesoscale wind profile.

4. Model Descriptions

ARL's mesoscale BFM model and micrometeorological HRW models have been coupled and integrated into the prototype simulation system. Navy Operational Global Atmospheric Prediction System (NOGAPS) (Bayler and Lewit, 1992) data were used to initialize the BFM. Other codes were also used to further analyze BFM output before the HRW input file was prepared. ARL's Atmospheric Sounding Program (ASP) (Passner, 1999) was used to establish mandatory levels as a vertical sounding profile. The Environmental Protection Agency (EPA)-approved CALMET, written by Earth Tech Inc. (Scire et al., 2000), was used to derive slope winds to enhance the analysis of BFM output used to initialize the HRW. Brief descriptions of the BFM and HRW models are provided, followed by a description of how the input and output are formulated.

4.1 The BFM

The BFM is a three-dimensional, hydrostatic mesoscale prediction model. It was designed to give improved wind data in the boundary layer and improve its forecasting by nudging to a larger-scale global forecast model. The model has typically been used with a grid spacing range from 2 km to about 20 km. The ARL BFM code (Henmi and Dumais, 1998) was adapted and customized from Yamada's Higher Order Turbulence Model for Atmospheric Circulations (HOTMAC) (Yamada and Bunker, 1989). The BFM core uses the Boussinesq approximation, an alternating direction implicit numerical scheme, and the Arakawa staggered C-grid. Prognostic equations for perturbed quantities of u , v , q ; virtual potential temperature, turbulence

length scale, and kinetic energy are solved on a timescale determined by wind speed and thermal stability. A sigma-Z terrain-following vertical coordinate system is used. Both pressure (Exner function) and the vertical wind component, w , are computed diagnostically. Pressure is computed from potential temperature and w is set equal to zero at the surface and at the top of the domain.

This project used the version of the BFM developed for Artillery meteorology, as reported in Haines et al. (1997). Using this version allowed us to take advantage of the flexibility of the surrounding software (CAAM). In CAAM, it was possible to make changes so that every time a target area forecast was called for, the HRW could be initiated. A target area was set up at the same location of the prior HRW efforts, and forecasts in the target area were made for every hour.

The CAAM BFM was configured for 32 vertical computational levels starting at 2 m and extending to 7 km above the highest terrain elevation. A 200 km-by-200 km horizontal domain was established using a 5-km grid resolution, and later repeated using a 2.5-km grid resolution (because the water regions in the San Francisco, CA, region were not well resolved at a 5-km grid spacing). The BFM was run out to a 12-h forecast and produced hourly outputs.

The input requirements included the following:

- Nudging data files from the larger-scale NOGAPS data files, updated every 12 h at a 1° resolution. (NOGAPS data were first acquired at a 2.5° resolution until it was determined that a 1° resolution was more appropriate for a 2.5-km BFM grid.)
- Creating an unsmoothed terrain file at the BFM resolution.
- Producing two user files for setting the physics and the timing.

These files are produced in CAAM in response to user inputs. The output is a single file of wind components, temperature, and a mixing ratio (called a “UVTQ” file) valid for all forecast hours. This output is then post-processed to form the input file required by the microscale model, including the required wind, temperature, and stability data at the required pressure levels valid at the center of the microscale grid.

4.2 The HRW

The HRW is a two-dimensional, diagnostic, time independent model that simulates airflow over complex terrain (including the effects of vegetation, buildings, and simple surfaces) with a high computational resolution, such as 100 m (40–400 m), and for a very local area, such as 5 km by 5 km (2 km to 20 km on a side), as described by Cionco (1985).

Physically, calculations are performed on an array of air parcels in a pressure field such that accelerations of these parcels are determined as they negotiate the changing slopes of the terrain and the added thermal lift or suppression component imparted by buoyancy. Computations are performed for the array of cells as flux boxes, defined by each four adjacent grid points and the underlying terrain-morphology surface. These calculations are completed in an iterative manner. Simulation values are obtained by direct variational relaxation of the wind field in the layer near the surface.

Numerically, the variational over-relaxation method is used to obtain a minimum of the combined acceleration forces in a pressure field. After the first iteration, the flow computations resolve changes of the field of accelerations over variable terrain with thermal lift and suppression effects. The solution is established when a minimum is reached, summing the change values over all the computational cells in the domain. The “vector of steepest descent” method is used during the calculations to approach the minimum. The solution is reached when the internal constraints forces imposed by the warped terrain surface, thermal structure, and requirements for flow continuity are minimized.

The procedure uses Gauss’ Principle of Least Constraints (Lanczos, 1962), which requires the forces to be minimized in order to satisfy the equations of motion. Mass is conserved during the calculations. Empirical wind and temperature vertical (structure) profiles are also used in the computational integration through the vertical thickness of the prescribed vertical layer.

As stand-alone code, the HRW is initialized with single values (at 10 m above ground level) for wind speed, wind direction, temperature, pressure, and buoyancy (stability computed from an upper-air sounding) derived from field observations or output from a coarser mesoscale model analysis. Digitized terrain elevation from DTED Level 1 is also required at each grid point within the area. Digitized land morphology datasets of land feature height, type, and footprint (Cionco and Ellefsen, 1998 and Ellefsen, 1985) are optional. The pressure and temperature fields are adjusted for terrain elevation throughout the domain before the simulation begins. The model’s output is composed of the u and v wind components, a vector field, a calculated streamline field, temperature, friction velocity, the Richardson Number, the Power-Law Exponent, and a partial component of the vertical motion (not always the total w component). Each parameter is calculated for the entire horizontal array and is tabulated and viewable with the appropriate graphics.

The HRW has been validated (Cionco and Byers, 1995; Cionco and Chang, 2000) using the Meteorology and Diffusion Over Non-Uniform Areas (MADONA) Field Study database (Cionco et al., 1999).

4.3 Other Models Employed

Additional models were required to perform this research: NOGAPS, ASP, and CALMET.

NOGAPS (Bayler and Lewit, 1992) is a global spectral prediction model typically run at a 2.5° resolution (however, at the time of this research, it was available at a 1° resolution). This model is capable of providing the nudging input files required by the mesoscale model. At the time of this report, there were several other models capable of giving this kind of input: the National Oceanic and Atmospheric Administration’s National Centers for Environmental Prediction (NCEP) Nested Grid Model (NGM); the North American Mesoscale (NAM) model; the Aviation (AVN) model; the Global Forecast System (GFS) model; the Rapid Update Cycle (RUC) model; the Air Force Mesoscale Model Version 5 (MM5); and the NCEP Reanalysis Program. However, intermediate software to reformat the output from these models is required for their use.

We decided to use the ASP (Passner, 1999) merely as a target of opportunity. The ASP was already required by the CAAM Met message program to provide target area weather from the BFM output. However, in the ASP algorithms to compute stability, there was software to extract information at mandatory pressure levels. So, the software to form the HRW input files for the required pressure level information was hidden in the ASP code.

The CALMET software (Scire et al., 2000) is a complete analysis and surface-wind diagnostics program. Although it could perform many of the tasks required for this prototype, it was only used in this early stage to provide a means to further modify the wind fields in complex terrain. While the microscale HRW program responds to terrain variations, severe complex terrain can overwhelm the vector-of-steepest-descent method. With a surface analysis (modified by the slope flow algorithm from CALMET) as the initial field, the HRW was able to more reliably reach a solution.

5. Discussion of Simulation Results

During the step-wise, manual execution of the codes, analyses were made for the U.S. Army MOUT site at Fort Benning, GA, as part of the WXWEB demonstration. An example set of solutions is shown in figures 1 and 2. For the San Francisco Bay area simulations, the target area was selected at Rodeo on San Pablo Bay, CA. Examples for 4 forecast hours are given for hours 0, 2, 4, and 6 in figures 3–7.

5.1 Fort Benning MOUT Site

The BFM solution is shown in figure 1 for 17 August 2000 at 1800 Zulu (Z) time (during the WXWEB demonstrations) for a domain of 200 km by 200 km (which has been zoomed to cover only about 58 km) at a 2.5-km grid resolution. The white square represents the 5-km box that is the HRW domain. Notice that although the flow is altered by the higher terrain (pink shading to the north and east of the site), there is very little flow curvature through the HRW domain.

Figure 2 shows the high-resolution analysis of the HRW as initialized by the BFM grid point, noted in the center of the HRW domain. The BFM's smoother wind field is further analyzed by the HRW with finer resolution to produce a more varied wind speed and direction field, shown as vectors and streamlines plotted over terrain contours (in red). The buildings of the MOUT site are located at the center of the HRW domain. The HRW clearly resolves more detail in the flow field as it interacts with the varying terrain elevation.

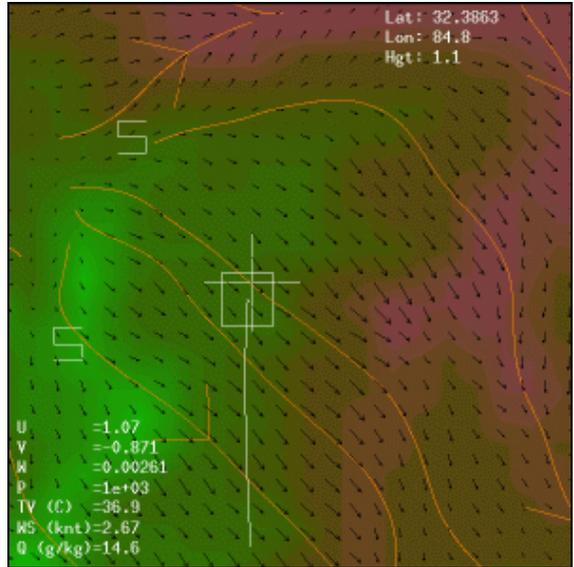


Figure 1. The BFM over the MOUT site on 7 August 2000 at 1800Z.

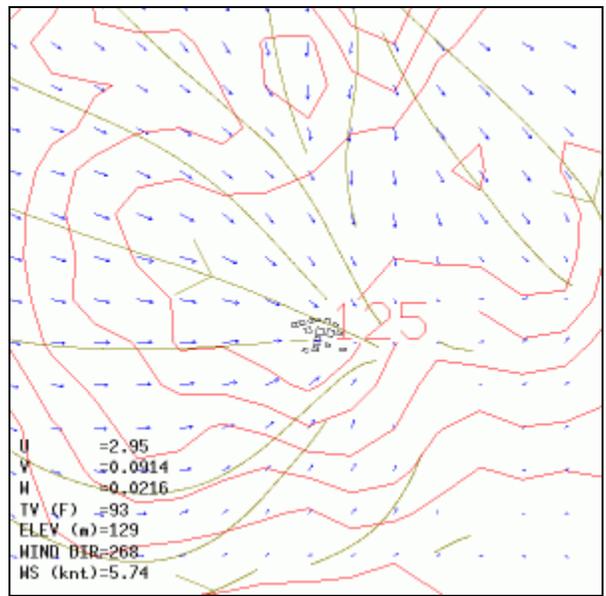


Figure 2. The HRW at the MOUT site.

5.2 Domains for Rodeo, CA

Figure 3a shows the BFM terrain configuration and figure 3b shows the HRW detailed terrain plot. The intent of figures 3a and 3b is to present only the terrain maps, not the accompanying streamline analyses and input data of hour 0. The BFM domain is 200 km by 200 km, while the HRW domain is 5 km by 5 km, with computational grids of 2.5 km and 100 m, respectively. The white-colored cross denotes the center position of the HRW domain and the input location for the BFM output. Met output data for each model (at the location of the cross) are noted in the lower-left corner of each figure. After this display, both the BFM and HRW will be enlarged and cropped to smaller areas in order to emphasize the details of each simulated solution.

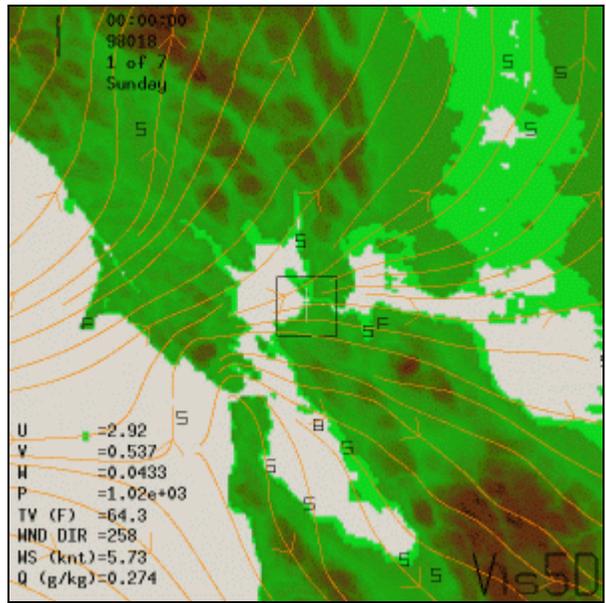


Figure 3a. The BFM domain for Rodeo, CA.

NOTE: The box indicates the domain of the HRW and the white cross indicates the center of the display.

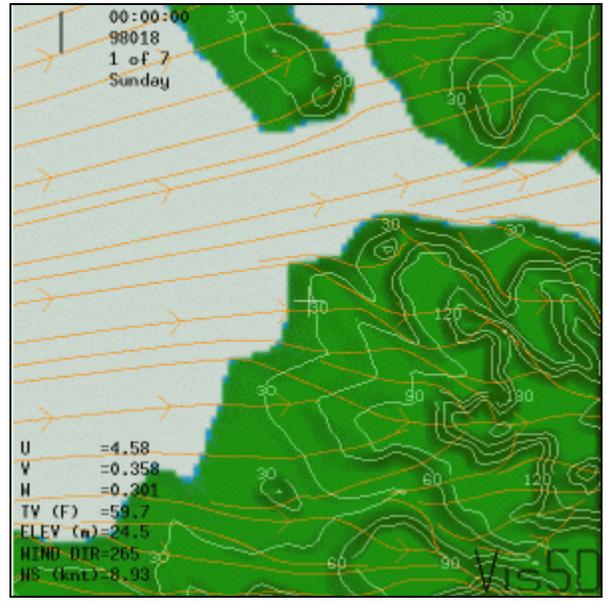


Figure 3b. The HRW domain for Rodeo, CA.

NOTE: The white cross indicates the center of the display.

Included in table 1 are values valid at the center point of the microscale model window (denoted by the white cross in figures 3a and 3b) derived from the BFM (to be used as input to the HRW), as compared to values computed from the HRW. This table shows wind speed, wind direction, and stability for the four hours of forecast reported. Note that while wind directions begin to conform to each other as time solutions progress, the wind speeds reported by the HRW are higher, perhaps reflecting a response to the more complex representation of terrain roughness.

Table 1. Simulation meteorological data.

Time	Stability	BFM Output to Initialize the HRW		HRW Output Values	
		Wind Speed (kn)	Direction (deg)	Wind Speed (kn)	Direction (deg)
Hour 00	Unstable	5.7	258	8.9	265
Hour 02	Near-neutral (slightly unstable)	2.1	170	2.5	217
Hour 04	Near-neutral (slightly stable)	3.7	136	4.8	136
Hour 06	Stable	3.8	129	5.2	129

5.2.1 Rodeo Output, Hour 0

The first hour of these simulations is noted as hour 0 (equal to 0000Z). Figures 4a and 4b show the enlarged and cropped BFM and HRW plots of vectors (black), streamlines (orange), terrain (shades of green), and water (gray) for San Pablo Bay, CA. The BFM's smooth flow field is for a 2.5-km resolution, while the more deformed HRW fields are for 100-m grids. The HRW's flow field during these unstable atmospheric conditions displays steering of the westerly flow over the water surface to become a northwesterly flow into the small valleys. There is also a notable deformation about the hill, located in the upper right corner, which is not resolved in the BFM solution.

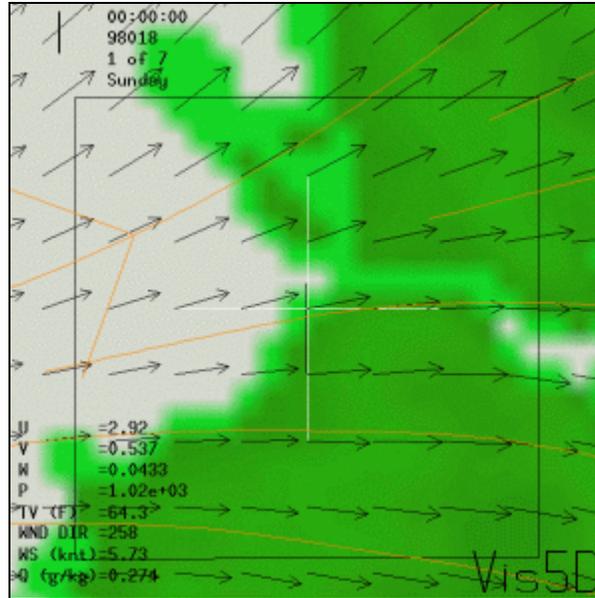


Figure 4a. The BFM at hour 0 (0000Z).

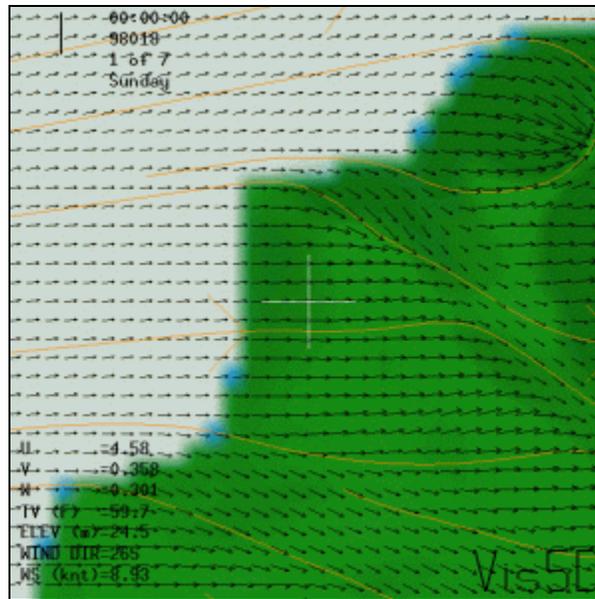


Figure 4b. The HRW at hour 0 (0000Z).

5.2.2 Rodeo Output, Hour 2

Hour 2 results are given in figures 5a and 5b in the same manner as figures 4a and 4b. The BFM's wind speed and direction have changed from hour 0, while the stability has approached a near-neutral condition (slightly unstable). The speed has decreased by a factor of 2 and direction has shifted about 90°, changing to a southerly flow. The BFM's flow field has more deformation than was produced during hour 0. The HRW speed field is somewhat enhanced, while directionally the valleys continue to affect the high-resolution field. The effects of the hill at hour 2 remain as dominant as they were at hour 0.

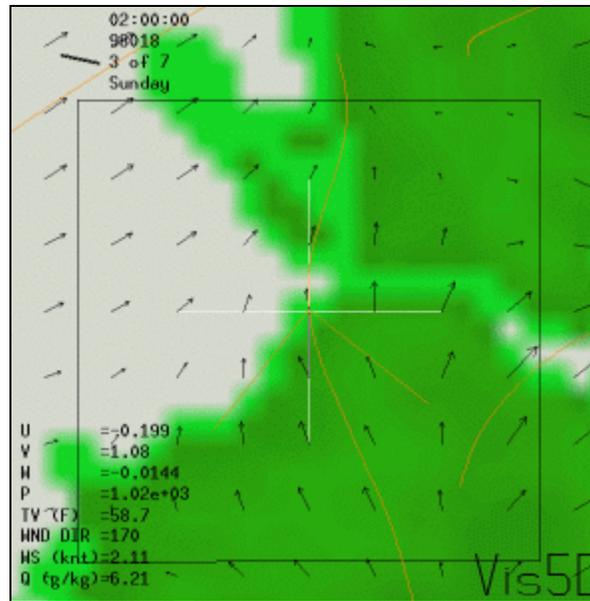


Figure 5a. The BFM at hour 2 (0200Z).

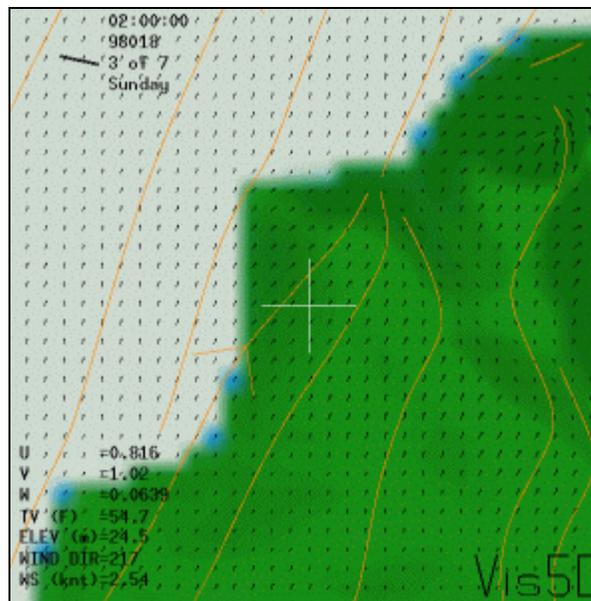


Figure 5b. The HRW at hour 2 (0200Z).

5.2.3 Rodeo Output, Hour 4

The hour 4 results (figures 6a and 6b) show that the BFM flow field has continued to shift directionally from previous hours, whereas the speeds have increased a bit. As the BFM flow shifts southeasterly (noted at the white cross) and the stability shifts to the slightly stable side of neutral, the HRW field now aligns with the valleys and produces minimum directional deformation. Some speed increases occur in the main small valley and about the hill area as before, due to the symmetry of the hill's contours.

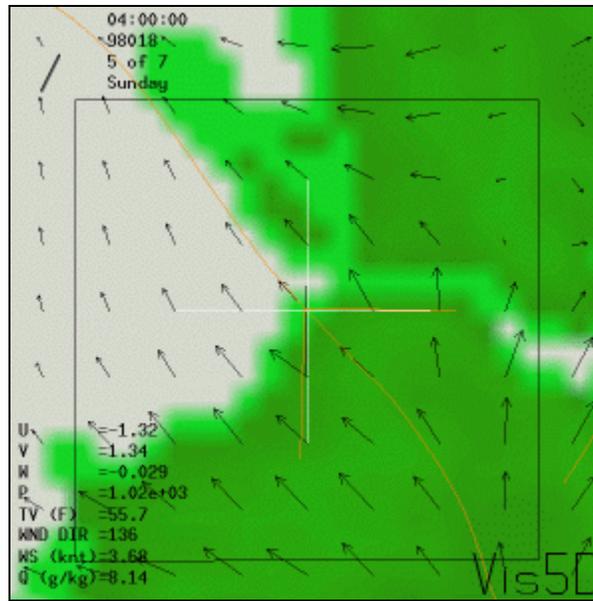


Figure 6a. The BFM at hour 4 (0400Z).

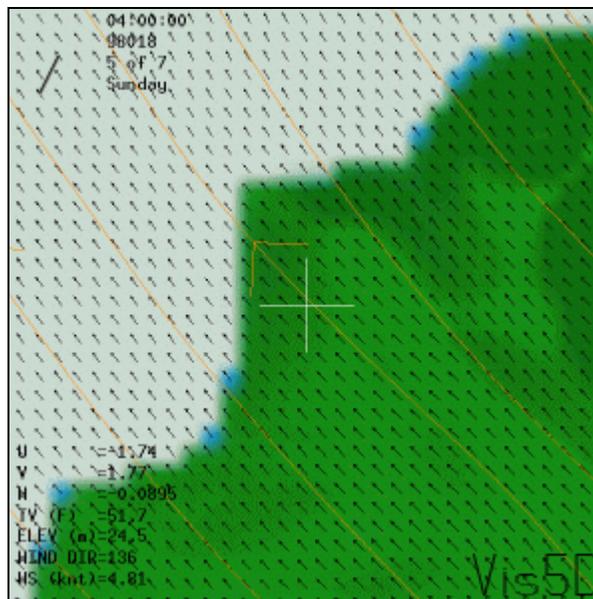


Figure 6b. The HRW at hour 4 (0400Z).

5.2.4 Rodeo Output, Hour 6

Starting at hour 4, as the HRW domain became more stable, the HRW winds tended to track the terrain less. At hour 6, although the BFM simulated wind fields shown in figure 7a reveal a little change in the streamline shape (the col in the NE corner of the box, denoting the HRW domain, has moved slightly to the SE), the HRW fields at hour 4, and at hour 6 (in figure 7b), show an almost straight-line flow and less diversity than the BFM. While the lack of

turning of the HRW flow in figure 7b with respect to the terrain is due to the stability, the lack of mesoscale features compared to the BFM is caused by the lack of diversity of the 16 grid points surrounding the white cross in figure 7a.

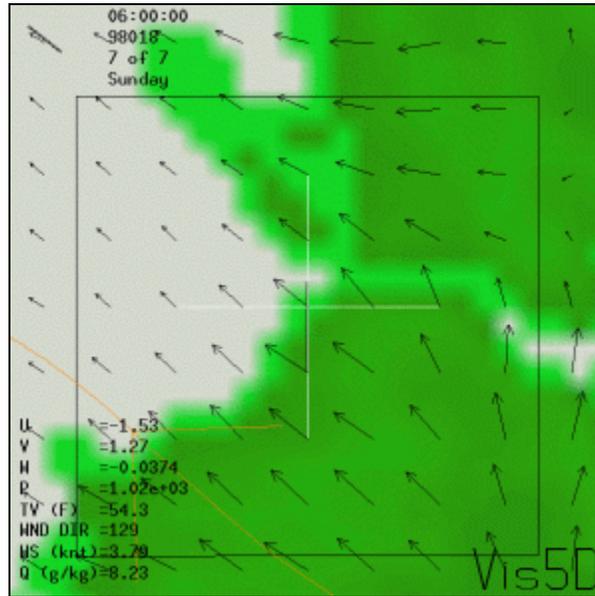


Figure 7a. The BFM at hour 6 (0600Z).

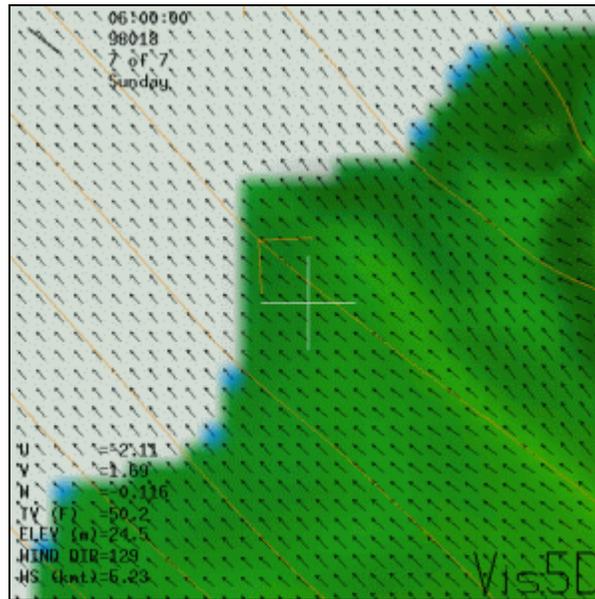


Figure 7b. The HRW at hour 6 (0600Z).

6. Conclusions

The first major step was completed with the BFM/HRW integrated prototype system running seamlessly in the Artillery program. The results of this modeling study provided several conclusions. Early in the integration study, it was apparent that higher-resolution inputs would be required. BFM simulations derived from a 2.5-km computational grid and a 1° NOGAPS initialization data field resolved more detail in the mesoscale flow field than was available with a 5-km grid BFM with a 2.5° NOGAPS initialization. With this higher-resolution mesoscale output, the HRW was able to generate a more detailed microscale airflow analysis in the target area. In the light wind and gentle terrain of the MOUT scenario, the HRW resolved significant terrain effects upon the speed and directional fields.

For the Rodeo, CA, domain, the output from hour 0 showed significant terrain influences in the unstable air and the favorable prevailing wind direction. This influence lessened as the wind speed decreased; the directions shifted and aligned more with the terrain; and the air became more stable. The HRW also exhibited different speed and direction enhancements as the BFM mesoscale winds shifted into different terrain alignment and slowed through the study period.

7. Future Research

It is clear that a quantitative evaluation of the coupled system of models is required as a future task. Subsequent to the research reported here, it was necessary to leave both the BFM and the Artillery modeling behind. The next step of research will focus on a stand-alone product that allows study in several directions:

1. Using the Canopy-Coupled Surface Layer (CCSL) model (Cionco, 1985) as a replacement for the HRW in order to capture the wind deviations caused by the surface morphology (land cover, land characterization).
2. Using other mesoscale forecast models that are supported by the research and operational communities.
3. Modularly adding transport and diffusion code to the execution string to better understand the effects of terrain and morphology on hazardous releases.
4. Adding the ARL knowledge gathered from this research into three-dimensional diagnostic microscale models.

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Acronyms

ARL	U.S. Army Research Laboratory
ASP	Atmospheric Sounding Program
AVN	Aviation
BFM	Battlescale Forecast Model
CAAM	Computer Aided Artillery Meteorology
CCSL	Canopy-Coupled Surface Layer
DoD	Department of Defense
DTED	Digital Terrain Elevation Data
EPA	Environmental Protection Agency
GFS	Global Forecast System
HOTMAC	Higher Order Turbulence Model for Atmospheric Circulations
HRW	High-Resolution Wind
Met	meteorological
MIT	Massachusetts Institute of Technology
MOUT	Military Operations on Urbanized Terrain
MM5	Mesoscale Model Version 5
MSS-P	Meteorological Sensor System- Profiler
NAM	North American Mesoscale
NCEP	National Centers for Environmental Prediction
NGM	Nested Grid Model
NOGAPS	Navy Operational Global Atmospheric Prediction System
RUC	Rapid Update Cycle
WXWEB	Lincoln Lab Smart Sensor Webs Project for the Weather Web
Z	Zulu time

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