P 4.5 Flow over a simple hill and its impact on wind speed, variability, and turbulence

Adam Kochanski*[1], Mary Ann Jenkins[2], Steven Krueger[1]

[1] Department of Atmospheric Sciences University of Utah

[2] Department of Earth and Space Science and EngineeringFaculty of Pure and Applied Science York University, Toronto, Ontario, CANADA

1. INTRODUCTION

Highly variable winds in complex terrain, together with dependence of the fire spread rate on the slope inclination, make prediction of the fire behavior in sloped terrain very difficult. In general, an enhanced fire spread rate in the uphill direction is attributed to flames being closer to the fuel on the uphill and the effect of fire-induced convection that also tends to push flames closer to the fuel. However, very little attention has been paid toward understanding the basic features of flow over a hill and their effects on the fire spread in terms of topographically-induced variability in wind speed and direction and turbulence. In this study we present the results of numerical LES (Large Eddy Simulation) of flow over an isolated hill and evaluate the results against available measurement data. We investigate surface, spatial distribution and variability of the surface wind speed and turbulent kinetic energy, the pattern of the surface flow, and the potential effect of the topographic flow on the variability in the fire line intensity.

2. METHODOLOGY

Our test case is of flow over the relatively smooth Askervein Hill. We chose this particular site because of its regular geometry, isolation from other hills, and most of all, because of the availability of measurement data collected during the Askervein Hill Project, described by Taylor and Teunissen (1983). The approximately elliptical Askervein Hill, located on the island of the South Uist (Outer Herbrides of Scotland), is 116 m high (126 m above the sea level), with a minor axis of around 2 km and the minor one of 1km. The topography of the hill, together with the LES model domain is presented in Fig. 1. The black line on this graph (crossing the hill top) represents the location of the line \`A' along which measurements used for validation of the LES results were taken. From the entire dataset collected during the Askervein Hill Experiment, we selected a subset corresponding to October 3rd, 1983, as a day considered to be the best measurement day of the entire field campaign. On this day the wind was strong, relatively steady, in the 210° direction, and blowing approximately cross the long hill axis. The data collected during this day were used for both model initialization and model validation.

*Corresponding author address:
Adam Kochanski, Department of Atmospheric Sciences, University of Utah
135 S 1460 E Salt Lake City, Utah 84112
e-mail: Adam.Kochanski@utah.edu

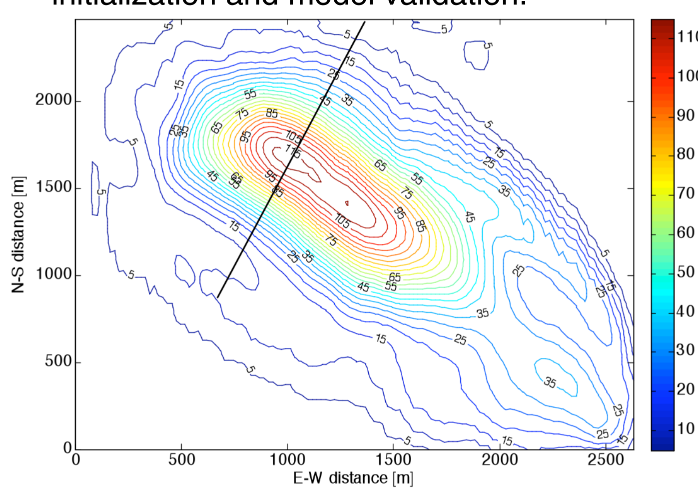

Fig. 1. Analyzed domain with the topography of the Askervein Hill (5 m contour intervals). The black line presents ‘A’ measurement line on which wind measurements were taken.

3. MODEL SETUP

The LES used was the University of Utah's LES model (UU LES). The UU LES is designed to simulate small-scale atmospheric flows that involve cumulus convection, entrainment, and boundary layer turbulence (Zulauf 2001). The dynamic framework is based on the three-dimensional nonhydrostatic primitive equations. The quasi-compressible approximation is used in which the speed of sound is artificially reduced. This allows for a highly flexible code, while still remaining computationally efficient. For this study, the model was setup for a 128x128x200 domain covering an area of 2650x2480x600 m (see Fig. 1). Cyclic boundary conditions were enforced in the UU LES. The model was run with the time step of 0.2 s, and provided a 1-hour long simulation with model data captured every 10 s. The model was initialized with potential temperature and relative humidity profiles obtained from on-site radiosonde measurements and from wind profiles from tower and kite measurements.

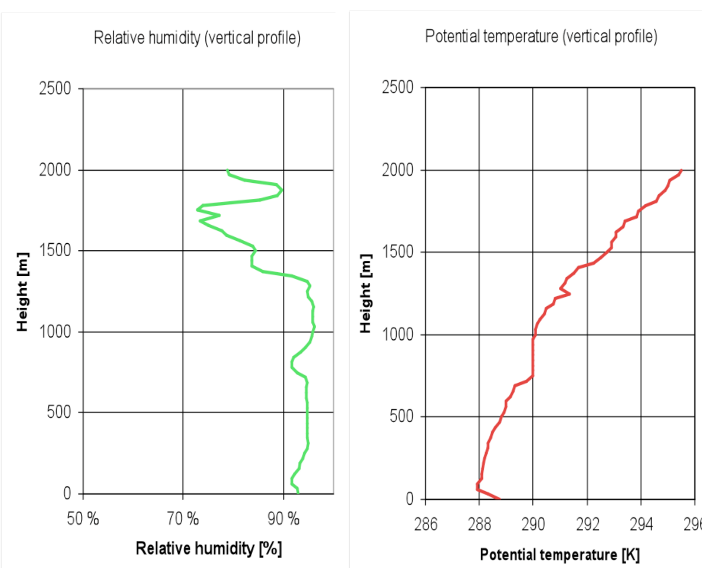

Fig. 2. Relative humidity (%), and potential temperature (K) profiles for 03.10.1983 (reference station).

The initial temperature and humidity profiles are presented in Fig. 2. Note that the atmosphere is relatively humid with the layer of high moisture extending to 1.3 km above ground level. The potential temperature profile indicates an unstable surface layer, capped by a strong inversion located around 90 m above ground level. Analysis of the wind field shows a mean wind speed during the day blowing from 210° direction at the speed of 18 m/s.

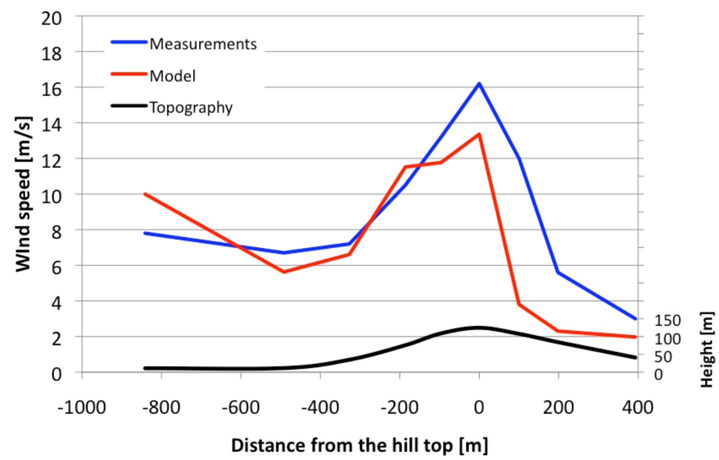

Fig. 3. Measured (blue line) vs. simulated wind speed (red line) across the long axis of the hill, with topography (black line).

4. RESULTS

The simulated wind speed was compared to wind speed measurements taken along the 'A' line (indicated in Fig. 1). The comparison between the measured and simulated wind speed across the long axis of the hill is shown in Fig. 3. The correlation coefficient between the simulated and observed wind speed was 0.75 with a mean absolute error (MEA) of 2.4 m/s. The model represented correctly the wind speed up on the upwind side of the hill. However, a comparison of model to observed data shows that the simulation has a drop in the wind speed on the leeward side of the hill that is too rapid. The evident shift between the simulation and observations (around 100 m lee of the hilltop) leads to noticeable MEA. There are several possible reasons for these discrepancies. A few are likely related directly to the UU LES. The model imposes simple periodic boundary conditions and does not allow turbulence feeding from external data or from a larger or outside domain. There is a lack of horizontal grid stretching, and very high-resolution topographical data (here we use 10 m resolution data). All these reasons can affect negatively the agreement between model and measured data. Therefore, in this case the UU LES cannot compete with more advanced model setups like those presented by Undheim (2006) or Golaz (2009) where 2 m resolution topography, horizontal grid stretching and domain nesting were used. In this study however, we do not focus on model performance. Instead, our objective is to be sure that the UU LES performs reasonably well before we use it to start looking at flow features important to fire propagation on the upwind side and on the lee side of the hill.

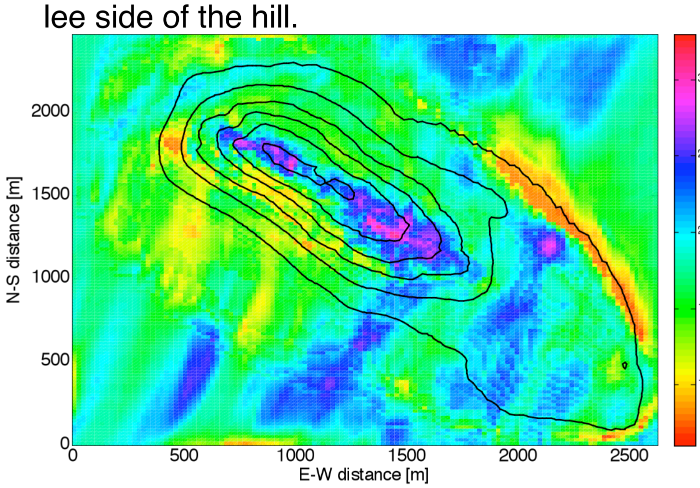

Fig. 4. Standard deviation of the simulated wind speed at 10 m above the surface (m/s), with topography contour lines (20 m intervals).

The first quantity to analyze is the wind variability, it is one of the most important factors that make fire behavior and spread difficult to predict, which does have a significant impact on the safety of fire fighters. For this study, as its measure we chose the standard deviation of the wind speed computed from model wind data taken at 10 s intervals. The results overlaid with topography lines (20 m intervals) are presented in Fig. 4. The standard deviations in the model wind field shows overlaid with topography contours, shows that the highest wind speed variability occurs along the hill's ridge and in the area just downwind from it. Over the highest parts of the hill, standard deviations of wind speed exceed 3 m/s. This result is reasonable since the highest part of the hill protruding above the inversion layer can generate strong eddies, increasing the turbulent character of the flow on the leeward side of the hill (Fig. 5).

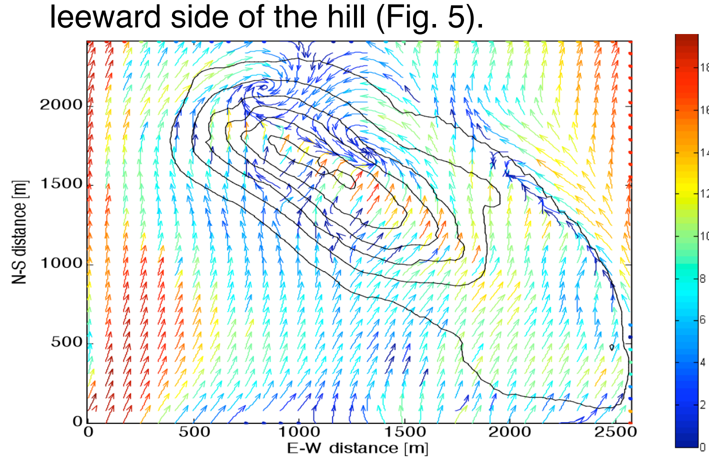

Fig. 5. Mean wind vectors at 10 m above the surface, with color-coded magnitude (m/s), overlaid with topography contour lines (20 m intervals).

However, the location of the second area of the highest wind speed variability is less straightforward. Contrary to the previous one, it corresponds to the relatively flat southeastern part of the hill. In this case, the wind speed variability maximum may be attributed to the development of cyclonic curvature in the flow that appears to be sensitive to the direction of the incoming mean wind. Slight variations in the direction of incoming flow can make this area either shaded from or directly exposed to the mean flow. Another possible reason may be the small irregularity in the hill topography northeast from this area.

The standard deviation of the model wind speed is a maximum around the hill top, with evidently higher values on the leeward side than on the windward side of the hill. This is consistent with measurements showing similar trend, but with more pronounced standard deviation increase on the leeward side of the hill.

In the case of the model turbulent kinetic energy, the spatial distribution is different. Fig. 6 shows a maximum of turbulent kinetic energy (TKE) on the windward slope of the hill, slightly ahead of its slope with much smaller TKE values on the leeward side. In this case the observed spatial pattern may be attributed to the stronger wind shear TKE production on the windward than on the leeward slope.

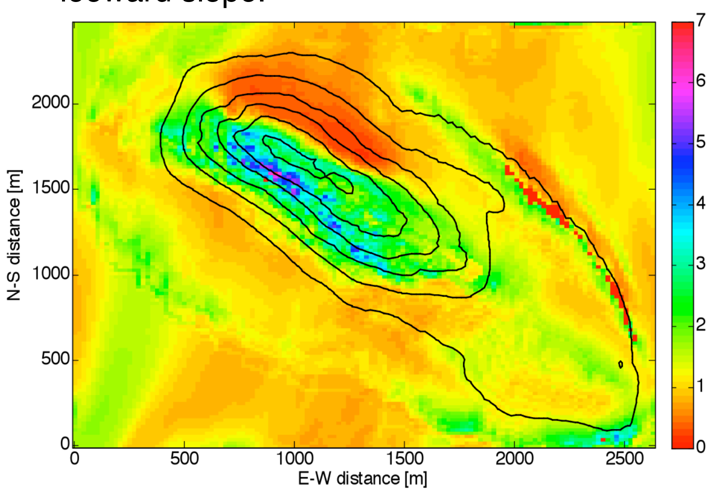

Fig. 6. Mean turbulent kinetic energy (m^2/s^2) simulated 10 m above the surface with topography contour lines (20 m intervals).

In order to evaluate the potential effect of the wind speed variability on the fire propagation, the fire line intensity was computed from the mean wind field using Roberts (1976) formula:

$$I = 17.5 \cdot U^3,$$

where I is the fire line intensity (kW/m), U is the wind speed (m/s).

As shown in Fig. 7, the spatial pattern of the fire line intensity is highly variable. The observed fire line intensity ranges from 77kW/m up to 26MW/m. The highest values are associated with the flow over the hill top where the highest wind speed up occurs. Other flow features, even of significantly lower mean wind speed, may also generate areas of enhanced fire line intensity. Also seen in Fig. 7, two locations corresponding to slight wind acceleration during flow around the southeast edge of the hill create two isolated areas of significantly greater fire line intensity, reaching in this case 1MW/m.

The pattern of the fire line intensity derived from the mean wind shows very high spatial variability, indicating the importance of the topography on the flow and subsequent fire propagation even without the effect of flame tilting

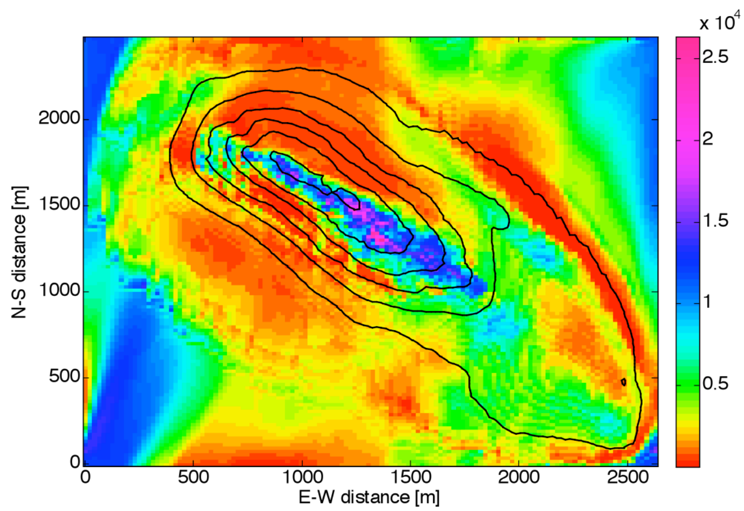

Fig. 7. Fire line intensity in KW/m computed from the mean wind at 10 m above the surface according to Roberts (1976) with topography contour lines (20 m intervals).

5. SUMMARY

Numerical simulations performed using the UU LES show that even relatively simple topography may induce very complex flow.

The highest parts of the hill evidently speed the flow up and induce strong eddies on the leeward side of the hill. Although not investigated, the upper level inversion layer may possible have had an impact on the evolution of the flow on the lee of the hill. The strong wind shear on the leeward side of the hill leads to an effective small-scale turbulence production that increases the TKE. In terms of impact on fire propagation, the highest fire spread would probably occur over the hill top where the mean wind speed reaches its maximum. However, even much smaller flow features, such as the two local maxima formed on the southeastern slope of the hill, may greatly increase fire line intensity.

REFERENCES:

Golaz J.,C., Doyle J.,D., Wang S., 2009, One-Way Nested Large-Eddy Simulation over the Askervein Hill, J. Adv. Model Earth Syst., Vol. 1, Art. #6, 6 pp.

Roberts Philip, J. W., 1979 Line Plume and Ocean Outfall Dispersion, Journal of the Hydraulics Division, Vol. 105, No. 4, April 1979, pp. 313-331

Taylor P, Teunissen H 1983 ASKERVEIN ’82: Report on the September/October 1982 Experiment to Study Boundary-Layer Flow over Askervein, South Uist, Report MSRB-83-8, Atmospheric Environment Service, Downsview, Ontario, 175 pp

Undheim, O.; Andersson, H.; Berge, 2006, E Non-Linear, Microscale Modelling of the Flow Over Askervein Hill, Boundary-Layer Meteorology, Volume 120, Number 3, September 2006 , pp. 477-495(19)

Zulauf, M. A., 2001: Modeling the effects of boundary layer circulations generated by cumulus convection and leads on large-scale surface fluxes. Ph.D. dissertation, University of Utah, Salt Lake City, 177 pp. www.met.utah.edu/skrueger/publications/zulauf_dissert_2001.pdf