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Coupled atmosphere-wildland fire modeling with WRF-Fire version 3.3 Supplement: A convergence study of the level set method

Jan Mandel[1], **Jonathan D. Beezley**[1], **and Adam K. Kochanski**[2]

[1]Department of Mathematical and Statistical Sciences, University of Colorado Denver, Denver, CO, USA
[2]Department of Meteorology, University of Utah, Salt Lake City, UT, USA

Correspondence to: Jan Mandel
(jan.mandel@gmail.com)

Abstract

We compare on several examples the convergence and volume conservation properties of the level set method as implemented in the code.

1 Introduction

This is a convergence study as requested by anonymous referee 1 of Mandel et al. (2011). We have set up several experiments to demonstrate the convergence of the level set method and the effect of artificial viscosity. In all experiments, the atmospheric domain was size 42×42, with mesh step 60m and homogeneous category 3 fuel (grass). The wind was initialized in diagonal direction from the upper right at 6m/s. Since the focus of the tests is on the level set method itself rather than the coupled model, the feedback to the atmosphere was turned off by setting the heat fluxes from the fire to zero. Several refinement levels of the fire mesh were tested, with the refinement ratios 1, 2, 4, 8, 16, and 32. The corresponding zero level set contours are drawn in progressively darker colors, yellow, green, magenta, brown, blue, and black, respectively.

2 Convergence tests

The first sequence of tests evaluates the ENO method of order 1 (the default) and Godunov's method (Osher and Fedkiw, 2003), with artificial viscosity (the default) as already in Mandel et al. (2009), and without artificial viscosity (Figures 1 – 4). These settings can be changed by the user. The fire perimeter was obtained by walking ignition, started at the point (510m, 990m) from the lower left corner and going up at the speed of 2.76m/s. Once the ignition reaches a particular point on the line, points in a circle growing at the speed of 0.9m/s are also ignited, until the circle of radius 40m is reached. We can see that in all cases, convergence is first order, as expected – the distance between the perimeters decreases by about the factor of two for every refinement of the fire mesh by the same factor. The runs with artificial viscosity appear to exhibit fewer artifacts and smoother perimeter evolution, especially for coarser fire meshes. There does not seem to be any significant difference between ENO and Godunov method.

The second series of test (Figures 5 and 6) evaluates the advection of a circular shape. The circle leaves a trace because the algorithm does not allow the level set function to increase. For this test, the spread rate was set to the normal component of the wind field, that is, the wind field acts as a pure advection. The version with viscosity developed an artifact for the refinement ratio of 16, and has grown unstable and did not complete for the refinement ratio of 32. However, this is an artificial test without any omnidirectional spread, which would otherwise stabilize the method. Note that the size of the advected circle is preserved, which would not be the case for the first-order method in time (Euler, not shown).

Finally, Figure 7 shows the level set function itself for illustration, and demonstrates the nonlocal character of the level set method – the advection of the smaller circle appears to affect the advection of the larger circle, as shown by the ridge in the values between them.

3 Conclusions

ENO and Godunov method gave almost identical results. The artificial viscosity had a slight advantage in a more realistic test, and a disadvantage in the artificial pure advection test. Nevertheless, the pure advection test is important because it has shown that the level set does not shrink over time; the lack of volume conservation is a well-known issue in level set methods, and sophisticated methods are usually needed (Enright et al., 2002). Other studies of volume conservation in the level set method were made early in the development of the code (Mandel et al., 2009), and they are reported in Kim (2011).

We consider a low-order numerical implementation of the level set method quite sufficient, because the uncertainties in the fire spread are much larger than the discretization error, particularly due to uncertainties in the fuels. The main reason why we have selected a low order method is that it requires much less communication when run on a parallel computer using the WRF parallel infrastructure. High order methods generally have much larger stencils and require wider halos and more frequent halo exchanges. This is a bottleneck in massively parallel computations, which are essential for running faster than real time.

References

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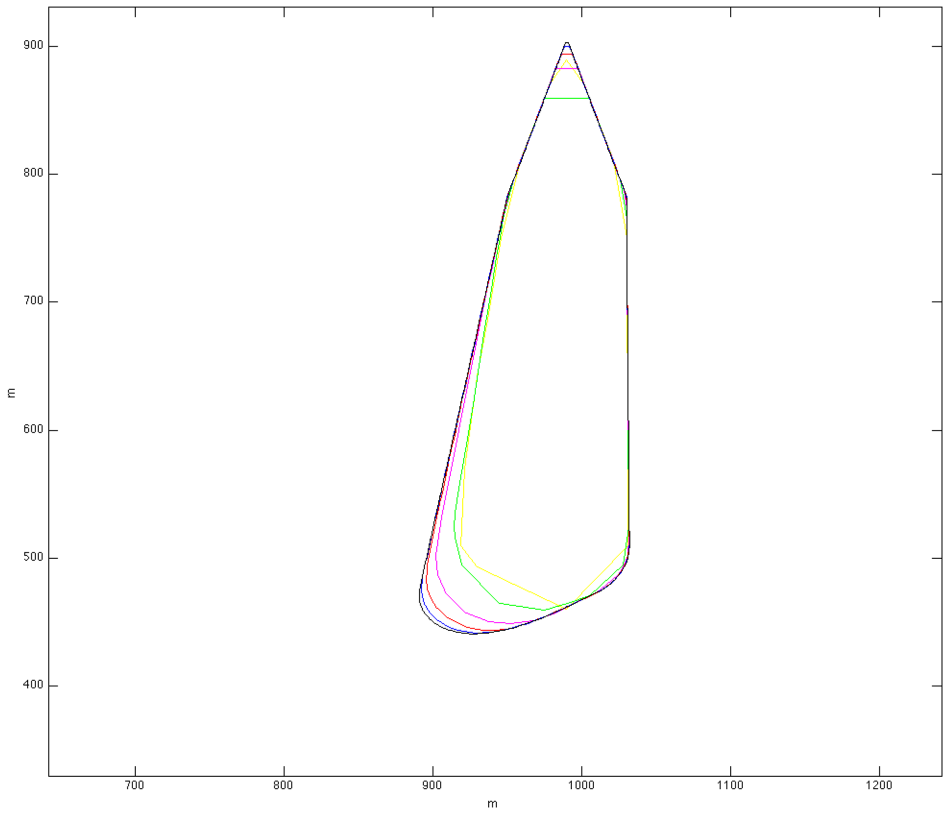

Fig. 1. Convergence of the fire perimeter for drip-torch ignition with first-order ENO with artificial viscosity (the default setting in the code). See the text for the description of the ignition line.

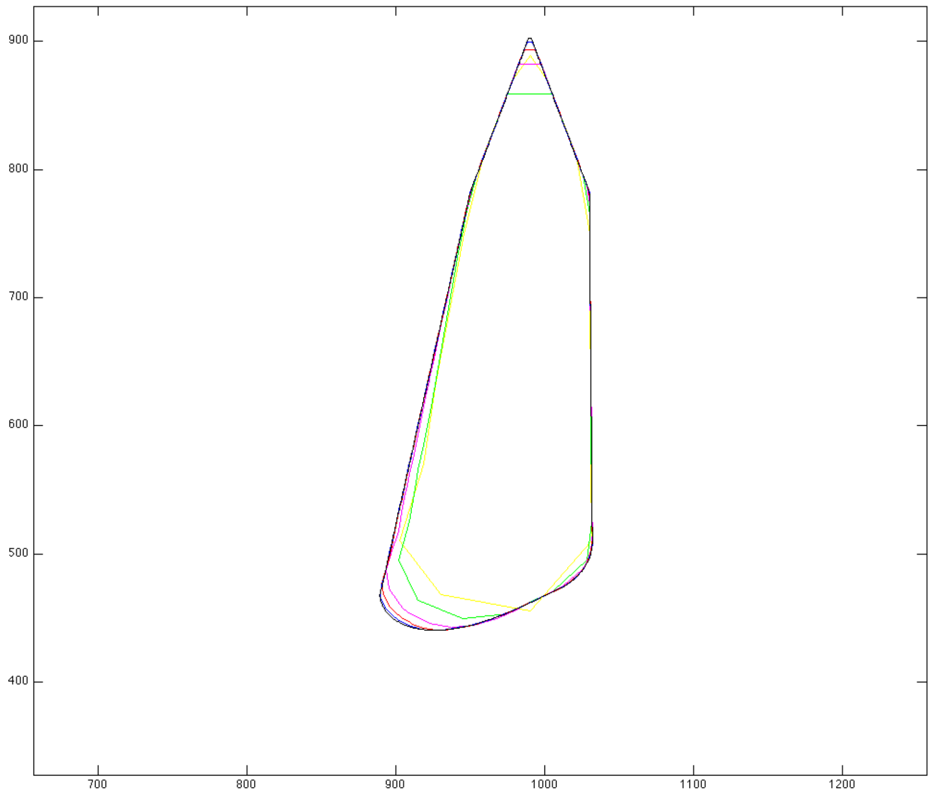

Fig. 2. Convergence of the fire perimeter for drip-torch ignition with first-order ENO without artificial viscosity. See the text for the description of the ignition line.

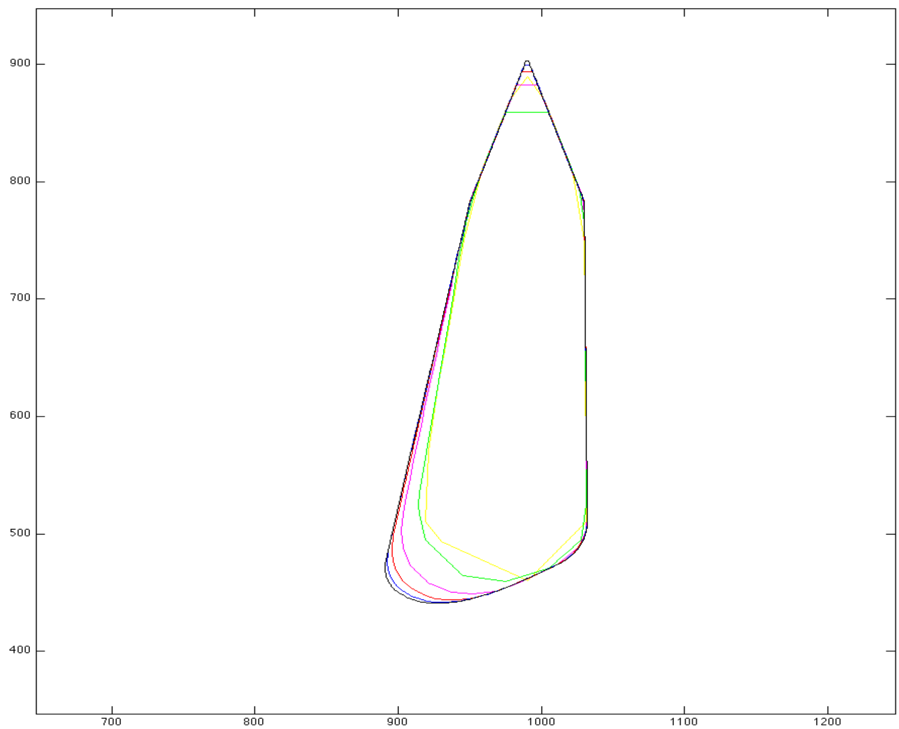

Fig. 3. Convergence of the fire perimeter for drip-torch ignition with Godunov method with artificial viscosity. See the text for the description of the ignition line.

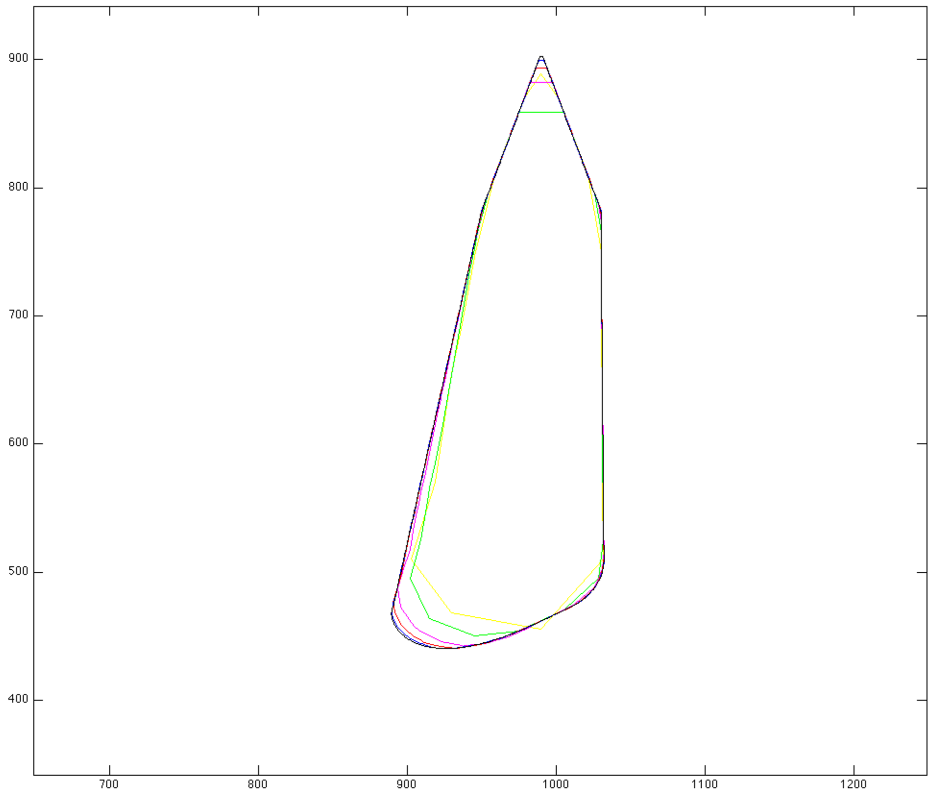

Fig. 4. Convergence of the fire perimeter for drip-torch ignition with Godunov method without artificial viscosity. See the text for the description of the ignition line.

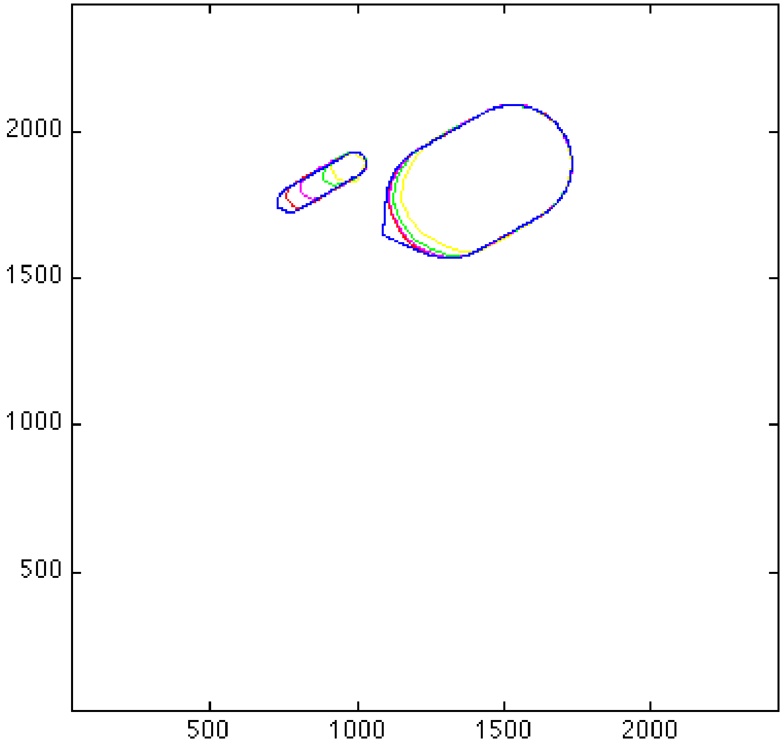

Fig. 5. Convergence for the advection of two circles, with artificial viscosity.

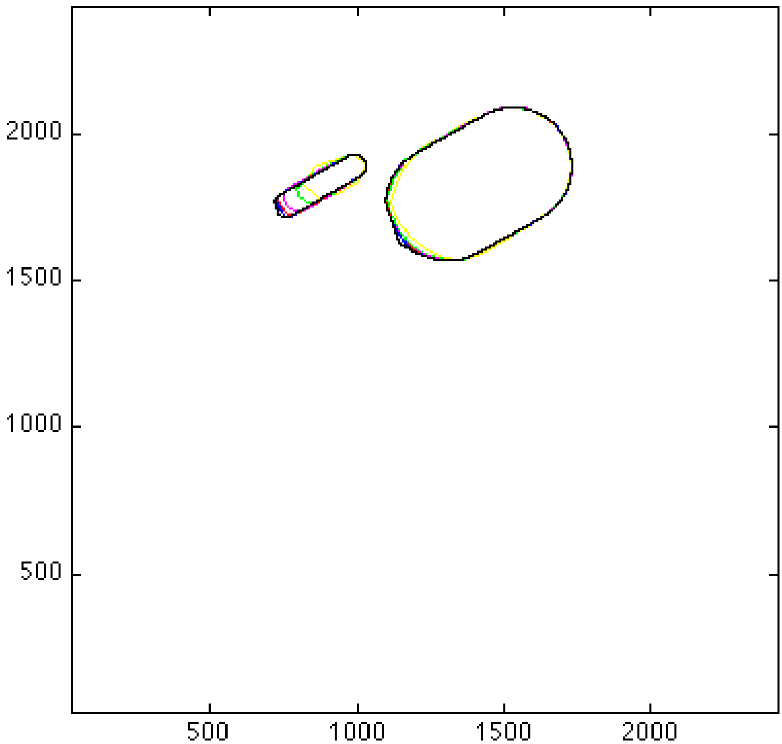

Fig. 6. Convergence for the advection of two circles, without artificial viscosity.

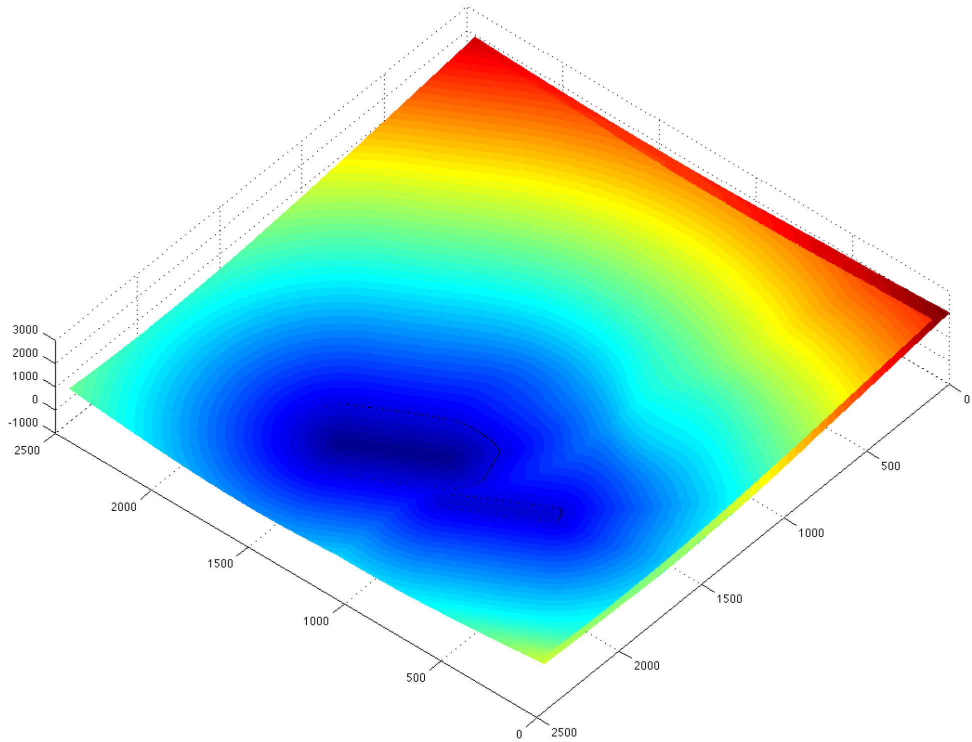

Fig. 7. Level set function for the perimeter in Figure 6.