QUIC-URB and QUIC-Fire Extension to Complex Terrain: Development of a Terrain-Following Coordinate System

David Robinson[1,2] Sara Brambilla[2] Michael J. Brown[2] Patrick Conry[2] Bryan Quaife[1] Rod R. Linn[2]

[1] Florida State University, [2] Los Alamos National Laboratory

Mountainous terrain is well-known to significantly affect the propagation of evolving wildland fires [4]. Terrain not only affects fire propagation by modifying heat transfer patterns due to varying geometry, but also the two-way feedback it has with motion of surrounding air. Wind-fire interaction is a major contributor to emergent fire behavior and thus an important phenomena to capture in order to correctly predict the behavior of wildland fires [2]. Topography changes these feedbacks through mechanisms occurring at a wide range of length and time scales. Furthermore, transport and dispersion of smoke plumes is of growing concern, especially in prescribed fire planning and execution [5], but the trajectory of plume movement is also affected by terrain. Accounting for terrain-induced effects on winds, and thus fire and smoke behavior, is an important piece of building a coupled fire-atmosphere model with sound predictive capabilities. The first steps in an extension of an existing diagnostic wind model, QUIC-URB, to a terrain-following coordinate system for use with an existing fire model, QUIC-FIRE, are described. A high resolution, 23 m, validation study using wind measurements over Askervein Hill demonstrates both successes and shortcomings of the model. The model shows good agreement with data in areas of open sloped terrain but lacks in areas where flow separation may be present.

Terrain-Following Coordinates	• $x = \tilde{x}$ • $y = \tilde{y}$ • $z = H\frac{\tilde{z}-h(\tilde{x},\tilde{y})}{H-h(\tilde{x},\tilde{y})}$	Contravariant Velocities	• $U^1 = \tilde{u}$ • $U^2 = \tilde{v}$, • $U^3 = \tilde{u}h_x\left(\frac{z-H}{H-h}\right) + \tilde{v}h_y\left(\frac{z-H}{H-h}\right) + \tilde{w}\left(\frac{H}{H-h}\right)$
Velocity Update	• $U^1 - U^1_0 = \frac{1}{2\alpha_1^2}\left[\lambda_x - \lambda_z\left(\frac{H-z}{H-h}\right)h_x\right]$ • $U^2 - U^2_0 = \frac{1}{2\alpha_1^2}\left[\lambda_y - \lambda_z\left(\frac{H-z}{H-h}\right)h_y\right]$ • $U^3 - U^3_0 = \frac{1}{2\alpha_2^2}\lambda_z\left(\frac{H}{H-h}\right)^2 - \frac{1}{2\alpha_1^2}\left(\frac{H-z}{H-h}\right)$ $\left[h_x\lambda_x + h_y\lambda_y - \lambda_z\left(\frac{H-z}{H-h}\right)\left(h_x^2 + h_y^2\right)\right]$	Integral to Minimize	• $E(U^1, U^2, U^3, \lambda) = \int_V \Big[\alpha_1^2\left(U^1 - U^1_0\right)^2 + \alpha_1^2\left(U^2 - U^2_0\right)^2$ $+\alpha_2^2\Big\{\left(U^3 - U^3_0\right)\left(\frac{H-h}{H}\right)$ $+\left[\left(U^1 - U^1_0\right)h_x + \left(U^2 - U^2_0\right)h_y\right]\left(\frac{H-z}{H}\right)\Big\}^2$ $+\lambda\left(\frac{\partial U^1}{\partial x} + \frac{\partial U^2}{\partial y} + \frac{\partial U^3}{\partial z} - \left(\frac{1}{H-h}\right)\left(U^1 h_x + U^2 h_y\right)\right)\Big] d\mathbf{x}$

Subscripts including letters correspond to partial derivatives of the respective direction (i.e., $h_x = \partial h/\partial x$).

Introduction

The development of QUIC-FIRE [8] was intended to provide an alternative to these computational fluid dynamics (CFD)-based tools that would be much less computationally expensive than FIRETEC/WFDSs [2, 6], which solve the full Navier-Stokes equations, models and yet represent some of the processes and three-dimensional structure of the fuel at meter scales. However, the wind solver underlying QUIC-FIRE, the Quick Urban & Industrial Complex wind solver (QUIC-URB) , does not currently include the influences of terrain on either the winds or the fire behavior. QUIC-URB is a diagnostic wind model that can produce mass-consistent wind fields from multiple, heterogeneous wind measurements over domains with sizes ranging from 1 km to 100 km at horizontal resolutions typically varying from 1–200 m [3]. The user can specify wind background profiles which QUIC-URB interpolates over its domain, the impacts of vegetative canopies and buildings are then parameterized and superimposed over the background wind [8], and finally mass consistency is imposed. The advantages of a diagnostic wind solver over its prognostic counterparts lie in its speed and memory requirements. QUIC-URB can generate wind fields for complex urban environments in less than 1 minute with a common laptop, i.e., it does not require super-computing capabilities.

Transformation & Methodology

To account for the effects of terrain-generated winds, terrain-following (TF) coordinates are adopted, denoted with (x, y, z) where H is the domain height at the point of lowest elevation and $h(\tilde{x}, \tilde{y})$ is the terrain elevation at $(\tilde{x}, \tilde{y})$. A transformation to contravariant velocities (U^1, U^2, U^3), simplifies the no-flux boundary condition enforced at the terrain surface ($U^3 = 0$). With these transformed velocities the integral minimized in QUIC-URB can be rewritten in contravariant terms. The Euler-Lagrange equation is then used to derive the velocity update equations and a mass conservation equation. By differentiating the velocity update equations and substituting them into the conservation equation the expression $\nabla^2\lambda = -2\alpha_1^2\nabla\cdot\mathbf{U}_0$ is acquired. The Lagrange multipliers, λ, that satisfy the equation minimize the integral shown above. To solve the equation the domain is discretized into cells where λ is cell-centered. Derivatives are represented with central-differences producing a sparse linear system that is solved using Successive Over-Relaxation (SOR). The SOR method is iterative where values of λ are updated via $\lambda^{(\ell+1)}_{i,j,k} = (1-\omega)\lambda^{(\ell)}_{i,j,k} + \omega\lambda'_{i,j,k}$ where $\omega \in (0, 2)$ is the relaxation parameter and

$$\lambda'_{i,j,k} = \frac{\sum_{i^*=i-1}^{i+1}\sum_{j^*=j-1}^{j+1}\sum_{k^*=k-1}^{k+1} C_{i^*,j^*,k^*}\lambda_{i^*,j^*,k^*}}{D_{i,j,k}} - \frac{2\alpha_1^2\left(\nabla\cdot\mathbf{U}_0\right)_{i,j,k}}{D_{i,j,k}} \quad \text{for } (i^*, j^*, k^*) \neq (i, j, k).$$

λ is iterated until $\frac{|\lambda^{(\ell+1)}-\lambda^{(\ell)}|}{|\lambda^{(\ell)}|} \leq 0.001$

Askervein Hill Study

The real world terrain feature, Askervein Hill (57°11.313 N, 7° 22.360 W) [1], with its simple geometry and isolation from surrounding terrain means that the missing physical dynamics in QUIC-URB, i.e., buoyancy and momentum effects, should not be a dominant factor in wind-field measurements. A comparison is made to measured data by using wind measurements during slightly stable atmospheric conditions (Richardson numbers between −0.0110 and −0.0074) along three transects at a height of 10 m that are provided in the MF03-D and TU03B datasets [1].A reference velocity of 8.9 ms^{-1}, 210° from North, measured at a location 3 km upstream, is used to set a power law vertical wind profile to match the profile data described in [7]. A vertical extent of 760 m is discretized by a stretched grid of 18 cells growing in height with increasing z.

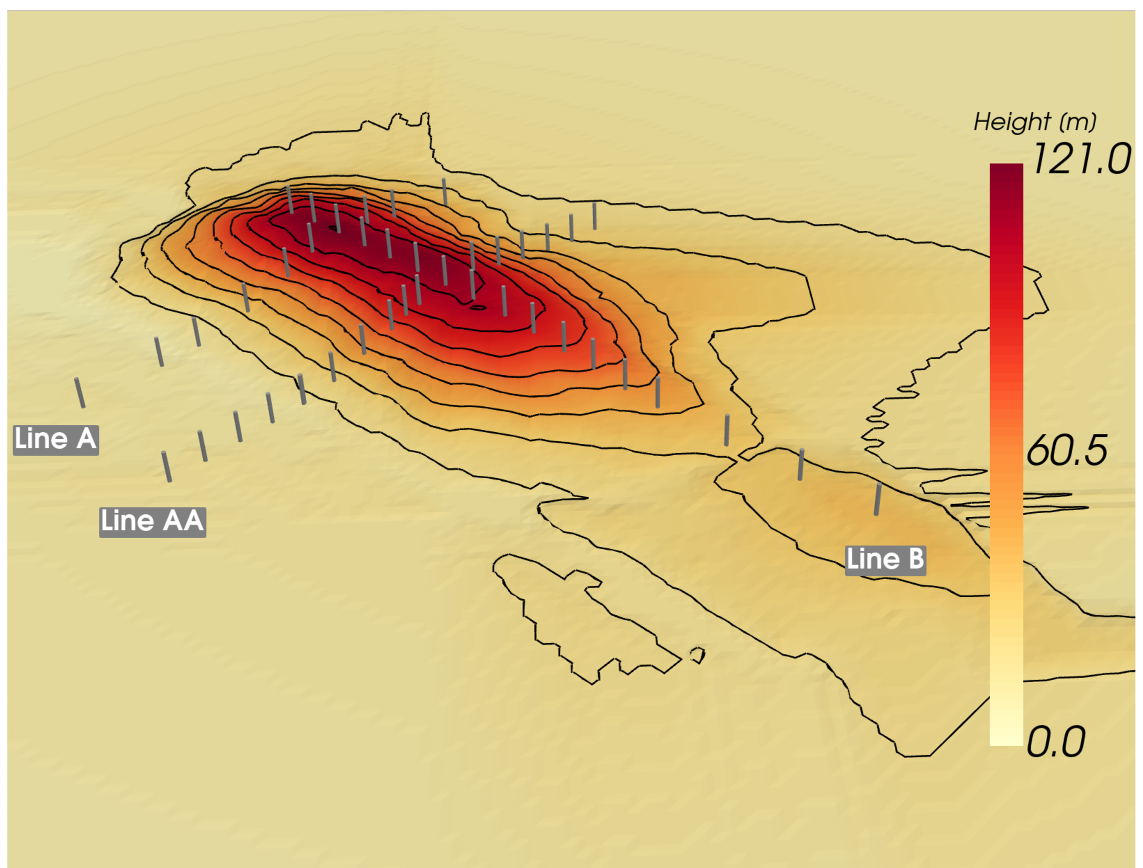

Fig. 2: A portion of the 6 km × 6 km, discretized into 257 × 257 horizontal cells, Askervein Hill domain. The transects are labeled by name with sensor locations being represented by vertical gray cylinders.

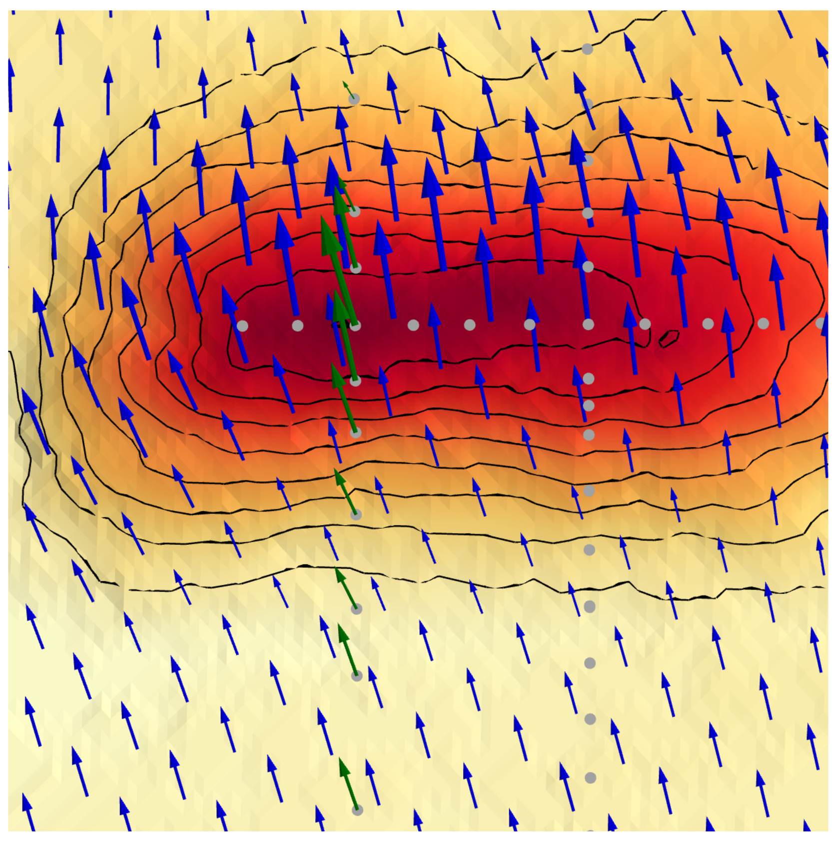

Fig. 3: A vector plot zoomed in over the larger hill of the Askervein domain. Sensor measurement vectors are colored green, and 20% of the surface winds from the QUIC-URB simulation results are colored blue. For visibility all vectors are scaled by a factor of 12.

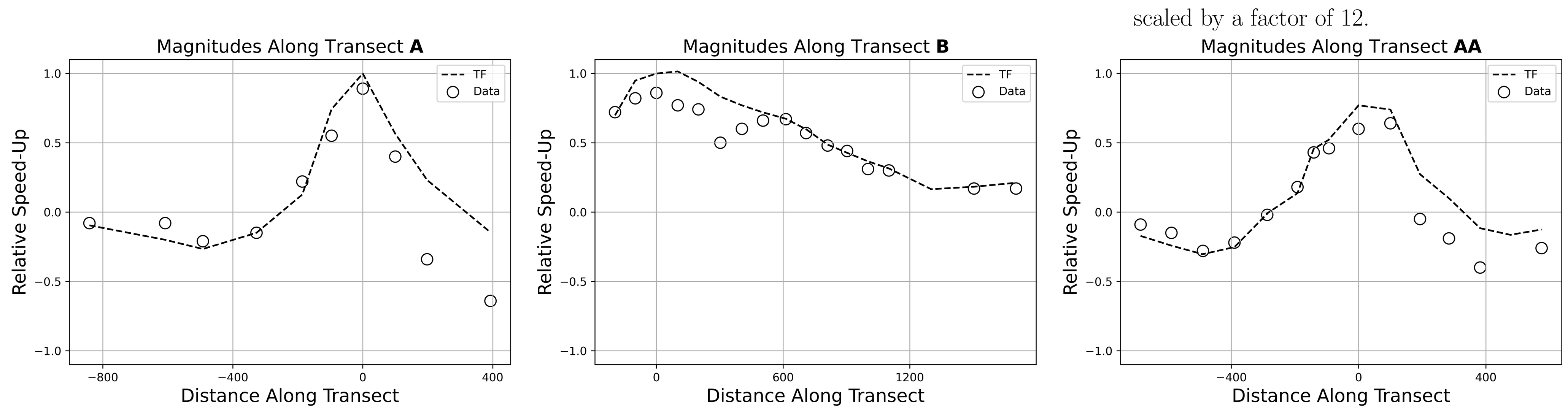

Fig. 4: A comparison of the measured winds and the results from the terrain-following implementation of QUIC-URB over Askervein Hill along transects A, AA, and B. These graphs show the distance along transect (distance of zero corresponds to the hilltop) vs. the relative speed-up from the reference upwind velocity. These results were produced using $\omega = 1.9$, with 349 iterations being executed on a laptop using 8 threads with OpenMP taking a total of 6 seconds.

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