3.6A Assessing topography and wind alignment for firefighter safety

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1. INTRODUCTION

Winds and topography are important components that dictate how wildland fires burn (Countryman 1972). Winds are quantified by both their speed and direction while topography is generally characterized by slope steepness and aspect. Wind speed and slope steepness have long been recognized as important factors governing fire spread (Fons 1946). Both factors improve the heat transfer between the burning front and fuels ahead of the fire and resulting faster spread rates and higher fire intensities (Byram 1959).

In addition to slope steepness and wind speed, topographic aspect, or the direction the slope is facing, and wind direction can interact to influence both fire spread rate and spread direction. Fires reach their maximum spread rates when winds blow directly uphill (Weise and Biging 1997). Fires generally burn uphill or in the direction of the dominant wind.

However, this situation is complicated when there are differences between the upslope direction and wind direction. When fires burn across complex terrain, they can burn into or out of areas where these factors are aligned thus causing abrupt shifts in fire behavior (Campbell 1998). These conditions are dangerous for wildland firefighters if they are positioned on steep slopes with unburned fuel between themselves and the flaming front.

Weather and topographic conditions can be observed on-site during fire operations but no methods exist to map hazardous alignment of environmental conditions *a priori*. General winds are commonly communicated as part of local weather forecasts but topography dramatically influences wind speed and direction across a landscape. Computational fluid dynamics simulations are now used to map these terrain-induced local wind flow patterns (Butler et al. 2006). High resolution wind maps produced by these simulations could be combined with topographic information to map areas where topography and wind direction align under prevailing general wind directions. These maps could guide fire fighters towards safer fire operations.

Here we present a simple trigonometric model that can be used to characterize the relationship between wind direction and upslope direction. It uses inputs of high resolution gridded wind direction from a computational fluid dynamics wind simulator (WindWizard) and an elevation map to delineate areas where topography and wind directions align. We use this method to illustrate the relationship between topography and wind in the 1994 South Canyon fire. This simple method can map topography and wind alignment *a priori* to improve firefighter situational awareness and safety.

2. METHODS

Angular Difference Model

In order to map topography and wind alignment spatially, we need a simple model that can easily determine the difference between wind direction and topography aspect (the direction the slope is facing). A simple angular difference made by subtracting the aspect direction from the wind direction would work in some cases but a simpler and more complete solution can be derived by using the following trigonometric identity:

$$\delta = \left|Sin(\frac{\phi_W - \phi_A}{2})\right| = \left|Sin(\frac{\phi_W}{2})\cdot Cos(\frac{\phi_A}{2}) - Cos(\frac{\phi_W}{2})\cdot Sin(\frac{\phi_A}{2})\right|$$

Equation 1

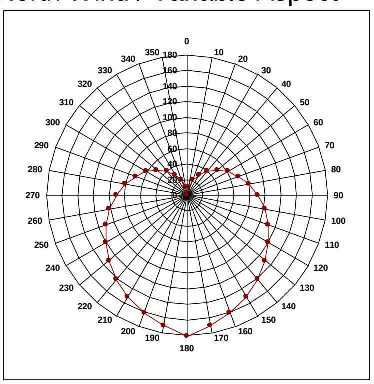
The resultant angular difference is defined as:

$$\phi_{DIFF} = |\phi_W - \phi_A| = ArcSin(\delta) * 2$$
$$0° \geq \phi_{DIFF} \leq 180°$$

Equation 2

Where Φ_W is the direction the wind is blowing from and Φ_A is the topographic aspect or direction that the slope is facing. Φ_{DIFF} is the angular difference between wind direction and aspect. All angles are assumed to be in radians but the result is converted to degrees to simplify mapping and communication. Because we are only concerned with the magnitude of the difference between the two angles, all values are forced to half of the unit circle and absolute values are taken so that the resultant angular difference between aspect and wind direction is always positive and bounded between 0° to 180° inclusive. Example plots of this relationship are shown in Figure 1 for a North and South wind and a variable aspect between 0° and 350°.

North Wind / Variable Aspect



South Wind / Variable Aspect

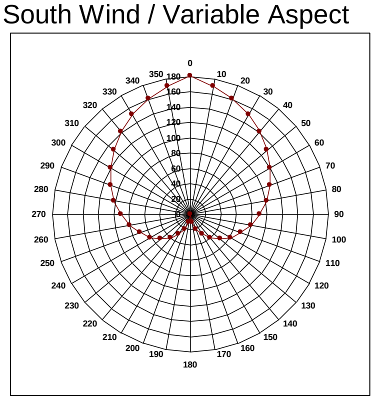


Figure 1 – Example plot of the angular difference between topographic aspect and a north wind (0°) (Top) and a south wind (180°) (Bottom). When aspect and wind direction perfectly align, values are 0° and when they are out of alignment values increase to 180°.

2.1 SOUTH CANYON FIRE EXAMPLE

High resolution wind simulations were performed for the area around the 1994 South Canyon Fire on Storm King Mountain in Colorado where 14 fire fighters were entrapped while fighting fire on steep, complex terrain (Figure 2). A complete discussion of the fire behavior associated with this fire can be found in Butler et. al. (1998). These wind maps were previously used to drive a fire spread model and these fire spread projections closely matched the estimated perimeters of the fire on the afternoon of July 6th during the time of the entrapment (Forthofer 2007).

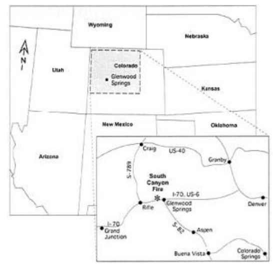


Figure 2 - Location of the South Canyon Fire (from Butler et.al. 1998).

For our example, we used the complex wind maps derived from a 270° general wind direction and the digital elevation model map used in the wind simulation. We resampled the elevation map to match the resolution of the gridded wind fields (50 meters) and used ArcMap Spatial Analyst extension to estimate the aspect of each grid cell.

Equations 1 and 2 were used to calculate the angular difference between aspect and wind direction for each grid cell across the study area. These differences were categorized into three classes: aligned, wind blowing cross slope or opposing. The class breaks are shown in

Table **1.**

Table 1 – Description of categories used to map the relationship between wind direction and aspect.

ϕ_{DIFF}	**Category**
0 to 45°	Topography and Wind Aligned
46° to 135°	Cross-Slope Wind
136° to 180°	Opposing topography and wind

Note: These class breaks are arbitrary and could be refined for local applications. For example, Rothermel (1983) suggests that topography and wind could be considered aligned when there is no more than +/- 30° difference between them. The results from the trigonometric model are continuous and bounded between 0° and 180° and these results could be classified in countless ways for display and mapping.

3. RESULTS AND DISCUSSION

A map showing the resulting aspect and wind direction alignment is shown in Figure 3. The map shows that winds either blew directly uphill or across the slope across nearly all of the study area at the time of fire fighter entrapment. A histogram showing the distribution of alignment values by pixel is show in Figure 4. Most angular alignment values were less than 60°, indicating that for the majority of the area, topography and winds were aligned. Based on the class breaks defined in

Table 1, topography and winds inside the burn perimeter were in alignment over 40.6% of the area, blowing across the slope over 56% of the area and opposing in only 3.4% of the area. These results are summarized in

Table 2.

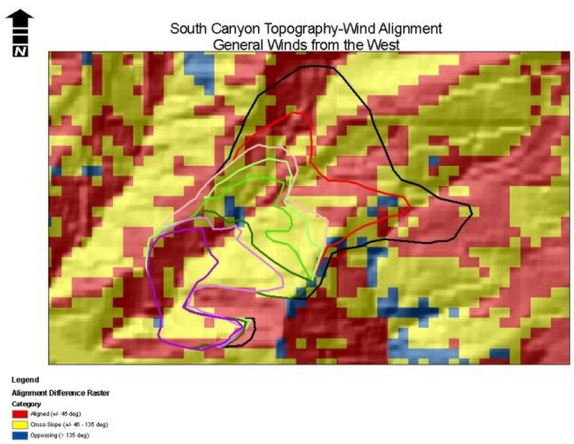


Figure 3 – Map showing the resulting alignment of aspect and wind direction during the 1994 South Canyon fire on July 6th. Colored polygons show the progress of the fire from 1602 to 1623 during the time of the entrapment.

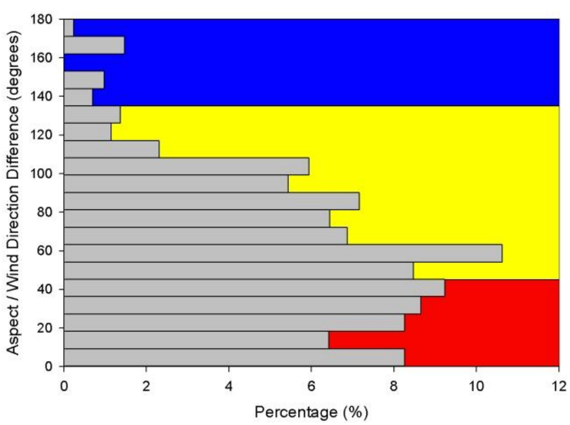


Figure 4 – Histogram summary of the angular difference between topography / wind within the study area. Blue / Yellow / Red shaded areas depict the category breaks used to create the map shown in Figure 4.

Table 2 – Summary of the percentage of all pixels within the burn perimeter that fall into each of the three categories.

Class Description	Percentage of total area (%)
Aligned	40.6
Cross Slope	56
Opposing	3.4

Although this method can adequately depict the alignment of topography and wind direction, it neglects the relative contributions of slope steepness and wind speed on fire behavior. A more complete formulation may take into account these factors by combining both the magnitude and direction components of topography and wind into a modified form of this metric.

One benefit of this method is that these maps can be created ahead of time, over a range of general wind directions to provide information of fire fighters about potentially hazards factor alignment before they arrive on scene at a new fire. This would provide additional information to assist them in implementing appropriate tactics to suppress a fire while ensuring fire fighter safety.

4. CONCLUSIONS

The methods presented here can be used to map the alignment of topography and wind direction across a landscape using inputs that are relatively straight forward to obtain. These maps can be created for various general wind directions ahead of time and can provide additional information about potentially hazardous alignment of wind and slope across a landscape. This information can be used to develop appropriate tactics to manage or suppress a fire while keeping fire fighters safe.

5. ACKNOWLEDGMENTS

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