Effects of Surface Wind Velocity Parameterization on Fire Spread Dynamics in Probabilistic Fire Model

David McCurdy

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Abstract

Understanding the role environmental factors have in wildfire spread has become increasingly important in the 21^{st} century. A large source of uncertainty in the propagation of a wildfire comes from effects of surface winds over the fires domain. Here we aim to constrain the effects of surface wind velocities on the rate of wildfire propagation. To achieve this we employ a numerical model using probability methods of propagation in order to evolve a wildfire through time while applying various wind velocity forcings. We find that surface wind velocities have significant effect on rates of wildfire propagation and provide a methodology to quantify this. Our findings signal the need for increased work in constraining the complex interactions between wildfire and wind in order to provide increasingly accurate information to first responders and the general public during wildfire emergencies.

1 Introduction

The occurrences of wildfires has become increasingly prevalent throughout the 20th and 21st century in domestic and urban areas. There are multiple factors that have contributed to this higher rate of threatening fires, from an abandonment of indigenous land stewardship−particularly in the western continental United States−increased development of homes and infrastructure in high risk areas, and more favorable conditions for fire ignition and propagation due to changes in regional climates brought on by anthropogenic CO_2 emissions. These increased occurrences necessitates understanding of how certain factors will affect the spread of wildfires over time, in order to assure public safety and minimize the destruction of property. A commonly known large influence on fire propagation is wind velocity over the wildfire domain. This is largely due to wind efficiently delivering oxygen to the fire helping to aid in combustion, and transporting heat and embers to new fuel sources. Here we investigate the effect surface wind velocities have on fire propagation using numerical modeling techniques, in order to better predict and constrain fire propagation for public safety.

2 Model

To investigate the role of surface wind velocities on fire propagation rates we used a a two dimensional probabilistic numerical model. The model evolves this fire over a two dimensional matrix of size (n, n) where n is an integer value. The model has three distinct types of propagation, a base propagation that is not dependent on wind, and two types of wind propagation: downstream and turbulent. The base propagation accounts for fire spread due to an immediate fuel source being adjacent to the fire, and can spread to any adjacent cell of an active fire cell. Downstream propagation is defined as the fire spread to a cell directly downstream of the wind vector direction, this cell is referred to as the downstream cell. The turbulent propagation is used to parameterize the turbulent and chaotic nature of wind velocities at this scale, and is defined as the fire spread to the two cells immediately adjacent to the downstream cell, that are also adjacent to the fire cell, these two cells are referred to as the turbulent cells. As a consequence of this propagation structure a fire cell can propagate in 3 discrete directions due to a wind forcing, and can propagate in 8 directions independent of wind.

This model makes further assumptions which will now be stated. The fire in a cell cannot go out once ignited. A non-time evolving wind field is used, which was chosen to observe a simple propagation scheme in order to understand the basic model response. For any wind direction ranging from 0-2π the fire can only spread to the 8 cells that are adjacent to the fire cell. The probability of fire propagation to these neighboring cells is calculated based on the ideas presented below.

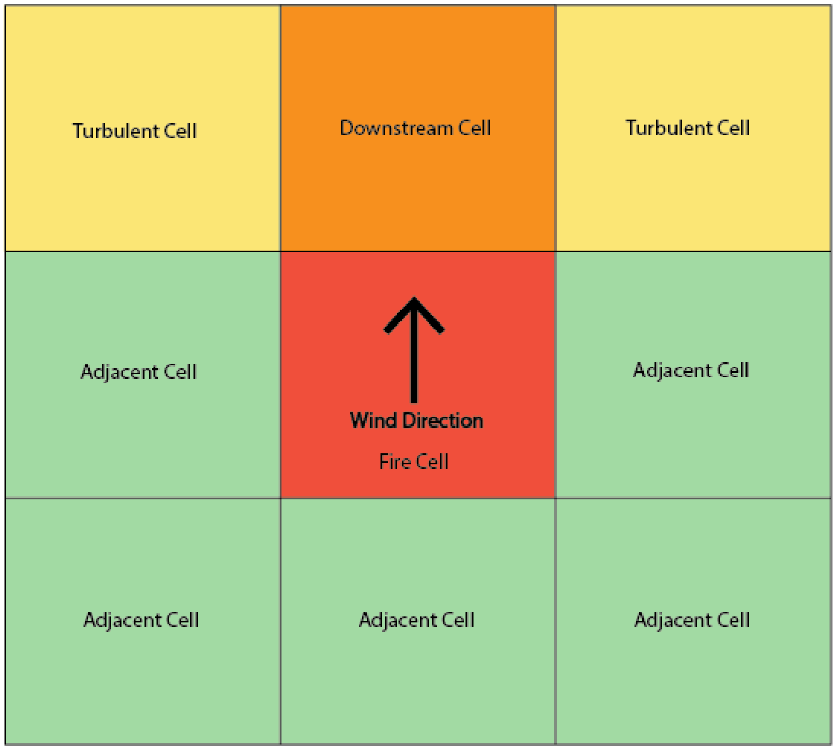

Figure 1: Here we see a simple case of a single active fire cell in red, and the corresponding downstream cell in orange and the turbulent cells in yellow for a defined wind direction. The green cells are adjacent cells to the fire cell that have only a base probability of propagation associated with them.

3 Methods

3.1 Overview

The model simulations will begin with an initialization of two matrices of equal size, a fire and wind matrix. Each cell in the wind matrix will contain a vector of the surface wind velocity over that cell in the fire matrix. The velocity will have a magnitude in m/s and a direction in radians ranging from 0-2π. The fire matrix will consist of only binary values, where a 0 represents a cell of no active fire and a 1 is a cell of active fire. The fire matrix will be initialized with a single cell on fire at a specified location. The wind vector values at all active fire cells will be evaluated. The 8 discrete directions will be assigned a range of values within the domain of 0-2π and the downstream and turbulent cell locations will added to their own lists. All adjacent cells to the active fire cells will be also be added to their own list. Then the items the three lists will be iterated through in three separate loops, starting with the downstream locations and ending with the adjacent locations. Within each iteration a random matrix will be created of equal size to the fire matrix, with a value between 0-1 in each cell. The respective probability value for each list will be evaluated against the random value at the corresponding location in the random matrix. If the random value is less than the probability value the cell in the fire matrix will be updated to have a value of 1. This method may result in multiple additions to the same fire cell, this at the end of all three of these iterations the fire cells with values greater than 1 will be assigned to be equal to 1. This new fire matrix will be saved and the next time step will begin. This process will be done for a set number of time steps. The state of the fire matrix at each time step will be saved in a list. This will be repeated a set amount of times to obtain a list of many runs. These runs will then be averaged to obtain the finished simulation.

3.2 Determining Probability of Wind Driven Propagation

Probability values ranging from 0-1 will be calculated using the magnitude of the wind vector in the fire cell. This will be done using the ad hoc relationship between wind speed and probability of downstream ignition:

$$p_d(|A|) = tanh(0.1|A|) \tag{1}$$

where p_d is the downstream probability of propagation and |A| is the wind speed in m/s. The turbulent probability value p_t is taken as 25% of the downstream probability:

$$p_t(p_d) = \frac{p_d}{4} \tag{2}$$

These relationships between wind speed and propagation probabilities are visualized in (Fig. 2).

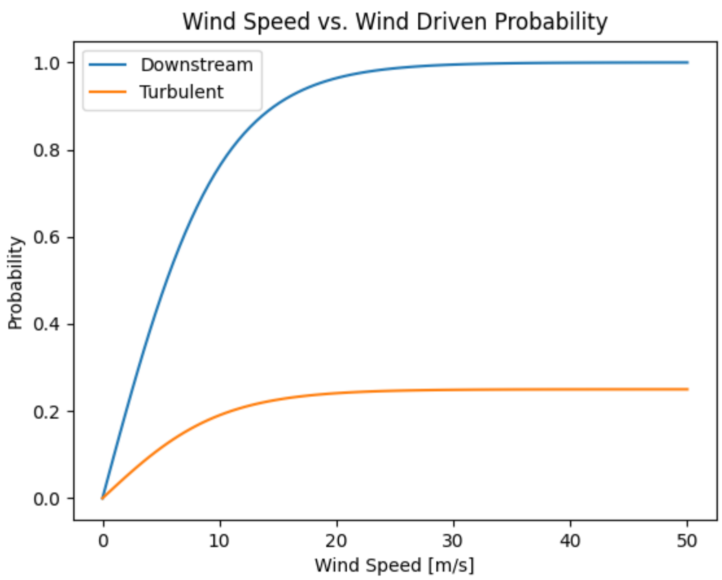

Figure 2: A visualization of the hyperbolic relationship between wind speed in m/s and probability of downstream and turbulent propagation.

3.3 Validation

3.3.1 Theory

To validate this model we will test its mean fire propagation value after 1 time step with an initial condition of two adjacent fire cells. The value of the probability grid for a single time step can be determined by analyzing the prorogation method and the following probability matrix can be obtained:

$$Fire\ Matrix : \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \end{bmatrix}$$

$$Corresponding\ Probabilities : \begin{bmatrix} (p_b)(p_t) & (2p_b)(p_d)(p_t) & (2p_b)(p_d)(p_t) & (p_b)(p_t) \\ (p_b) & / & / & (p_b) \end{bmatrix}$$

The slashes are disregarded cells in this example since they are already active fire cells. Then we can solve analytically for the probability of the mean fire propagation using the formula:

$$P(n, p_b, p_d, p_t) = 1 - (1 - p_b)^n (1 - p_d)(1 - p_t) \tag{3}$$

Here P is the general probability in a given cell and n is the number of fire cells adjacent to it and p is our probability value. If a cell does not contain either a downstream or turbulent probability that value effectively becomes 0 and its corresponding term in the equation goes to 1. Solving for this for these cells we obtain:

$$P(1, p_b, p_d, p_t) = 1 - \prod_{i=1}^{3}(1 - p_i)$$

$$P(2, p_b, p_d, p_t) = 1 - (1 - p_b)^2(1 - p_d)(1 - p_t)$$

Where i denotes the three probability values in the product series.

3.3.2 Numerical v Analytical Solutions

For $p_d(|\mathrm{A}|)$ where $|\mathrm{A}| = 1$ m/s we obtain $p_d = 0.099$ and thus a $p_t = 0.025$, and have set $p_b = 0.2$. Plugging this into our fire matrix from above we obtain the corresponding probabilities for each cell:

$$Analytical : \begin{bmatrix} 0.22 & 0.44 & 0.44 & 0.22 \\ 0.20 & / & / & 0.20 \end{bmatrix}$$

Now we will compute this probability matrix from our model that is averaged over 10,000 runs:

$$Numerical : \begin{bmatrix} 0.219 & 0.442 & 0.433 & 0.220 \\ 0.198 & / & / & 0.199 \end{bmatrix}$$

Our error for each grid cell is:

$$Error : \begin{bmatrix} 0.004 & 0.0004 & 0.016 & 0.0 \\ 0.0 & / & / & 0.005 \end{bmatrix}$$

These error values do not exceed a standard tolerance level of 0.05 and thus we can conclude that this model is valid.

3.3.3 Downstream Propagation Rates

In order to determine the downstream propagation rates used in this study we isolated the column, row or diagonal in the fire matrix that the wind vector is pointing in, we will use a northward flowing wind matrix as an example:

$$Wind\ Matrix: \begin{bmatrix} \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\ \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\ \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \\ \uparrow & \uparrow & \uparrow & \uparrow & \uparrow \end{bmatrix}$$

With an initial fire matrix:

$$Fire\ Matrix: \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

Thus our column of interest will be the column containing the initial fire cell.

Once this column is isolated we define the edge of the fire. We define the fire edge as the downwind position where the mean fire matrix value drops below a defined threshold value. For this study we used a value of 0.7. We then iterate through every time step of the fire matrix evolution in the column and add its position in the row to a list at each time:

$$J: \begin{bmatrix} j_1 & j_2 & j_3 & ... & j_n \end{bmatrix}$$

Where j is the row number of the fire edge, the subscript n is the iteration number, and J is the list of positions of the fire edge through time. Our downstream propagation rate is defined as the change in position over the change in time:

$$V = \frac{j_{n+1} - j_n}{t_{n+1} - t_n} \tag{4}$$

4 Result

The model was run with a wind field and without a wind field. The fire propagation relative to a fixed point within the domain was compared between the two runs, the output of these two runs is shown in (Fig. 3).

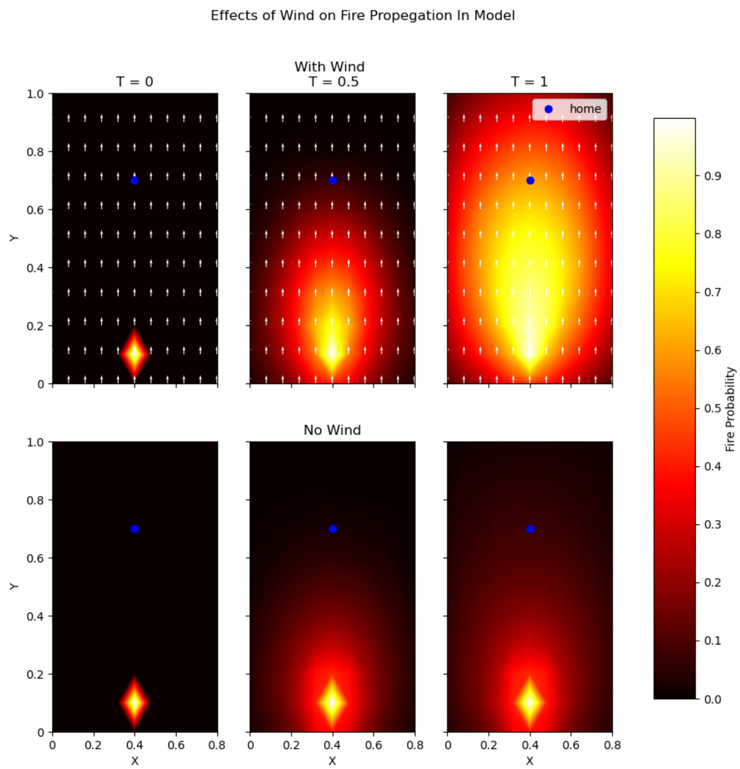

Figure 3: Here are two runs, the top row shows the runs with a northward wind vector field that can be seen in white, while the bottom row shows the fire propagation with no wind forcing. The columns show the state of the model at three stages in the runs denoted by T: the beginning, middle and end of the simulation. The averaged probability values are shown in the contour color bar. The blue dot in all plots is the fixed point that is at the same position in both experiments. Here it represents a home to illustrate the importance the difference in propagation has to lives and property.

The results show that the wind forcing has an impact on the rate of propagation of the fire. This can be seen most prominently when comparing both simulations at T=0.5. In the wind forced experiment the fire has reached the home (blue point) by the middle of the run, while in the no wind experiment the fire has yet to reach the home. This shows that if the effects of wind are not considered in the model, the time of evacuation may not be correctly determined by local agencies and this leads to risk of public safety.

Next we show the downstream rate of fire propagation for three different wind forcings.

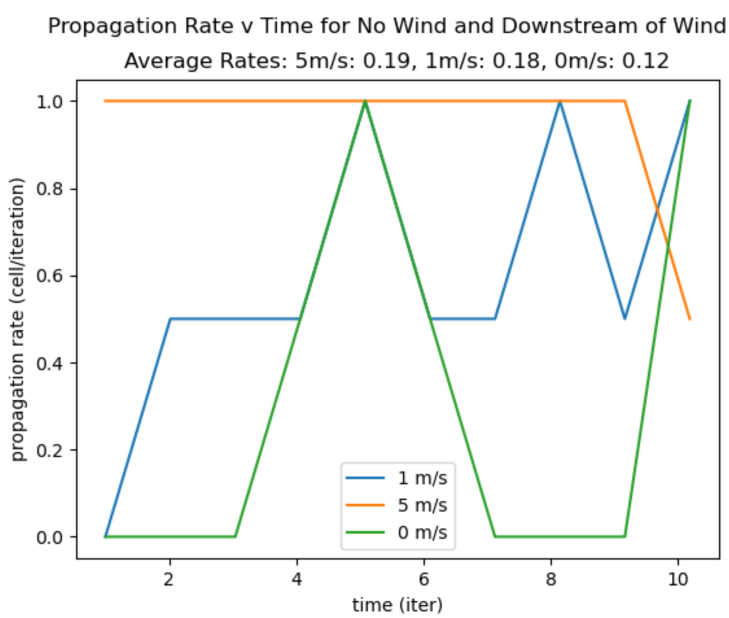

Figure 4: This figure shows the downstream propagation rates for three different wind forcings: 5 m/s, 1 m/s and 0 m/s or no wind. The x axis is the number of model iterations, represented as time in our simulation, while the y axis is the propagation rate which is the cells propagated to per time step of the model. The average rates for each run are shown above the figure.

In (Fig. 4) we observe that as the wind speed increases the downstream propagation rate increases. The average rates show this, with a increase in the rate of propagation going from 0 to 1 m/s of 50%, while going from 1 to 5 m/s shows an increase of 5.6%. The results show a larger variation between 0 m/s and 1m/s than between 1 m/s and 5 m/s. This implies that accounting for the presence of wind is the most important consideration, however this may come from the model design and the probability values used, and should be tested against similar models and real world data

5 Discussion & Conclusion

The effects of surface wind velocity on the rate of fire spread is observable, quantifiable, and significant in understanding how a wildfire will evolve in real world scenarios. Visually interpreting our results show that wind forcings can lead to fires reaching vulnerable areas faster than if no wind forcing is applied. We created a methodology for quantifying the propagation rate, providing a way to preform detailed analysis on the model response to wind, and in doing so we found that the effects wind has on fire propagation is significant. Our study found in order to respond most effectively to wildfires, surface wind velocities must be considered.

The model has several caveats, such as the relationship between wind speed and probability of ignition being assumed and not empirically determined which would effect the propagation rates and the change in propagation rates for a change in wind speed. The non-linear effect that fire would have on the surface wind velocities is not considered in the model such as creating hot plumes of air rising upward that will effect local pressure gradients resulting in fire induced winds and vortices. Incorporating it would account for otherwise unpredictable fire spread. Future work should be done to address these caveats, such as constraining the relationship between wind speed and probability of ignition using real world data. Addressing other dynamics in the model that come from wind should be considered in order to study the effects of wind on fire propagation, such as embers transported past the fire edge and creating new ignition sources elsewhere which would result in large uncertainties in propagation if not accounted for. A time evolving wind field, and a wind field responding to the fluid dynamic effects of heat generation by the fire would help to further parameterize the physics that govern fire spread.

In conclusion, this study set out to answer the question of how surface wind velocity effects the rate of fire propagation. The study found a significant relationship between wind speed and propagation rate showing that this is an important factor when considering wildfire spread in real world scenarios. As we move into a future of more prevalent and intense wildfires studies such as these will prove to be paramount in saving lives and property.