4.4 Simulating Diurnally Driven Slope Winds with WindNinja

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WindNinja is a simple diagnostic model designed for simulating microscale, terrain-influenced winds. A recent addition to WindNinja is a diurnal slope flow model. The model uses sensible surface heat flux, distance to ridge top or valley bottom, slope steepness, and surface and entrainment drag parameters to compute a diurnal slope wind. The diurnal wind can be combined with the ambient gradient winds. Testing of the model on a simple, hypothetical hill shows reasonable qualitative results. Fire spread simulations using FARSITE and the diurnal model show that the diurnal winds have some effect on predicted fire spread. The addition of the diurnal model is expected to be a simple, useful tool for fire analysts.

1. INTRODUCTION

Wind is one of the most influential environmental factors affecting wildland fire behavior (Catchpole, Catchpole *et al.* 1998; Rothermel 1972). The mountainous terrain typical of many wildland fires produces complicated local wind patterns that make fire behavior prediction difficult. Accurate prediction of these wind patterns is necessary for accurate fire behavior predictions.

Until only recently, operational fire behavior analysts had no tools available to predict micro-scale winds in mountainous terrain. They were forced to rely on broad-scale weather forecasts that generally did not include localized terrain effects. The analyst typically had to use intuition to determine how the broad-scale forecasts would be influenced by local factors such as mechanical flow modification due to terrain, diurnal slope and valley flows, atmospheric stability effects, and sea/land breezes. Also, fire behavior models such as FARSITE (Finney 1998) were forced to assume wind was spatially uniform.

Currently, at least three micro-scale wind models have been developed specifically for the wildland fire community. They are WindStation (Lopes 2003), WindWizard (Forthofer 2007; Forthofer, Butler *et al.* 2003), and WindNinja (Forthofer 2007). These models are built with simplified interfaces that allow fire behavior analysts and other fire personnel to perform simulations with little training. Also, the models are able to run on personal computers rather than large multiprocessor systems.

The convenience of these fire-specific wind models, however, comes at a price. The models must make simplifying assumptions that limit their applicable range. For instance, all the models assume neutral atmospheric stability. In reality, the atmosphere is rarely exactly neutral, but is often near neutral especially in the lower regions of the atmospheric boundary layer. In these cases, the neutral assumption becomes an approximation with some associated error. In atmospheric stabilities far from neutral, however, this error can become so large that the simulation is useless. Other important assumptions of the wind models are that diurnal flows are negligible, the inlet boundary condition can be easily specified by a single wind speed profile, the coriolis force is negligible, and moisture effects are negligible. Similar assumptions are used in other emergency response situations such as accidental or deliberate release of radiological, biological, or chemical hazards into the atmosphere when quick turnaround time is essential (Homicz 2002).

The purpose of this paper is to describe new features added to WindNinja to reduce its assumptions and increase its applicable range. These new features are the inclusion of a diurnal slope flow model and a micrometeorological model to estimate atmospheric stability, surface heat and momentum flux, boundary layer height, and other

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boundary layer parameters necessary for the slope flow model. Diurnal slope flows are most important when gradient winds are low.

2. MICROMETEOROLOGICAL MODEL

The micrometeorological model used in WindNinja closely follows that of Scire and Robe (1997) and Scire, et al. (2000) for the CALMET model, with some deviations. Some of the equations are repeated here for clarity and to show differences. The main parameters computed are the surface heat flux (Q_h), Monin-Obukhov length (L), and boundary layer height (h).

Sensible surface heat flux is computed using the energy budget model of Holtslag and van Ulden (1983). The energy balance can be written as:

$$Q_* + Q_f = Q_H + Q_e + Q_g \qquad (1)$$

where, Q_* is the net radiation (W m^{-2}),
Q_f is the anthropogenic heat flux (W m^{-2}),
Q_h is the sensible surface heat flux (W m^{-2}),
Q_e is the latent heat flux (W m^{-2}), and,
Q_g is the storage/soil heat flux (W m^{-2}).

The net radiation is computed using the parameterization of Holtslag and van Ulden (1983):

$$Q_* = \frac{(1-A)Q_{sw} + c_1 T^6 - \sigma T^4 + c_2 N}{1 + c_3} \qquad (2)$$

where, T is the measured air temperature (degrees K),
σ is the Stephan-Boltzmann constant (5.67 x 10^{-8} W m^{-2} K^{-4}),
c_1 is 5.31 x 10^{-13} (W$m^{-2}K^{-6}$),
c_2 is 60 (Wm^{-2}), and,
c_3 is 0.12.

The incoming shortwave radiation, Q_{sw}, is computed by:

$$Q_{sw} = (a_1 sin\varphi + a_2)(1 + b_1 N^{b_2}) \qquad (3)$$

where, $sin\varphi$ is the direct solar radiation on a slope (W m^{-2}),
φ is the solar elevation angle (degrees),
N is the fraction of the sky covered by clouds,
a_1 is 990 (W m^{-2}),
a_2 is -30 (W m^{-2}),
b_1 is -0.75, and,
b_2 is 3.4.

In WindNinja, the direct solar radiation on a slope is computed using the algorithm from the National Renewable Energy Laboratory (2000). A custom shadow computation has also been implemented to account for terrain shadows.

Anthropogenic heat flux, Q_f, in (1) is set to zero. The relation

$$B = \frac{Q_h}{Q_e} \qquad (4)$$

where, B is the Bowen ratio, is used for the latent heat flux, Q_e. Lastly,

$$Q_g = c_g Q_* \qquad (5)$$

is used to compute the storage/soil heat flux term, Q_g. c_g is an empirical parameter dependent on the properties of the surface. Using equations (1) – (5), the sensible surface heat flux can be computed.

Once the sensible surface heat flux is computed, the Monin-Obukov length, L, and surface friction velocity, u_*, can be computed. For positive sensible heat fluxes, L and u_* are computed iteratively as in CALMET using:

$$u_* = \frac{ku}{ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right) + \Psi_m\left(\frac{z_0}{L}\right)} \qquad (6)$$

$$L = \frac{-\rho c_p T u_*^3}{kgQ_h} \qquad (7)$$

where, z_0 is the surface roughness length (m),
Ψ_m is a stability correction function,
k is the von Karman constant (0.4),
u is the wind speed (ms^{-1}) at height z,
T is the temperature (K),
c_p is the specific heat of air at constant pressure (m^2 s^{-2} K^{-1}),
ρ is the density of air (kg m^3), and
g is the acceleration of gravity (m s^2).

If the surface sensible heat flux computed from (1) – (5) is negative, the model of van Ulden and Holtslag (1985) for nighttime conditions is used to compute L and u_* and recompute the surface sensible heat flux.

Next the atmospheric boundary layer height, h is computed. For positive sensible heat fluxes, the boundary layer height is assumed to be equal to a computed neutral atmospheric boundary layer height (Blackadar and Tennekes 1968; van Ulden and Holtslag 1985):

$$h = 0.2\frac{u_*}{f} \qquad (8)$$

where f is the so called Coriolis parameter computed using the latitude of the center of the modeling domain. Note that this is different than CALMET, which also computes a convectively driven mixing height and chooses the atmospheric boundary layer as the greatest of these two. Since this second computation requires a vertical temperature profile from sounding data it was not included in WindNinja because sounding data is not easily available to fire analysts. This omission is hoped to have little effect on simulated surface winds in most cases. The stable boundary layer height is chosen as the minimum of (8) and (van Ulden and Holtslag 1985; Zilitinkevich 1972):

$$h = 0.4\left(\frac{u_* L}{f}\right)^{\frac{1}{2}} \qquad (9)$$

Lastly, the stability correction functions in (6) are computed using methods described by van Ulden and Holtslag (1985). The vertical wind speed profiles used in WindNinja are:

$$U(z) = U(z_1)\frac{ln\left(\frac{z}{z_0}\right) - \Psi_m\left(\frac{z}{L}\right)}{ln\left(\frac{z_1}{z_0}\right) - \Psi_m\left(\frac{z_1}{L}\right)} \qquad (10)$$

Where, U is wind speed (m s^{-1}), and,
z_1 is the measurement height of a specified wind speed $U(z_1)$.

3. SLOPE FLOW MODEL

The slope flow model used in WindNinja is the shooting flow model of Mahrt (1982). It is implemented the same as in CALMET (Scire and Robe 1997; Scire, Robe *et al.* 2000), and thus will not be described in detail here. In essence, the slope flow model is a one-dimensional model of buoyancy driven flow along a slope. The magnitude of the slope flow is a function of the acceleration distance, percent slope, surface and entrainment drag parameters, and surface sensible heat flux. It is implemented in three dimensional models such as CALMET and WindNinja independently at every surface grid cell. The acceleration distance for down slope flows is computed as the distance to the ridge top, and for upslope flows the distance to the valley bottom. This distance is computed in WindNinja by simply traversing a line defined by the particular slope and aspect at the cell in question until a valley or ridge is found. The direction of the slope flow is exactly upslope or downslope as defined at the cell. The depth of the slope flow is assumed to be 5% of the elevation difference to the ridge or valley.

WindNinja computes wind fields by first initializing the flow domain using (10) and a user specified input wind speed and direction. Then the slope flow component is computed and added to the initialized values. Last, the WindNinja solver is run which solves for a divergence free flow (mass-conservation) while minimizing the change from the initial flow field (including slope flow parameterization). Details of this last step are described in Forthofer (2007).

4. MODEL SIMULATIONS ON AN IDEAL TERRAIN

To demonstrate the effect that the diurnal flow model has on overall wind and fire behavior calculations, a simple ideal hill has been constructed. The hill is defined by:

$$E(r) = \frac{H}{1 + \left(\frac{r}{L_h}\right)^4} \qquad (11)$$

Where, $E(r)$ is the elevation (m) at distance r (m) from the hill top,
H is the height of the hill above sea level (m),
L_h is the horizontal distance (m) from the hill top to a point where the hill elevation is $\frac{H}{2}$.

In these simulations, H was 600 m (970 ft), L_h was 2400 m (7900 ft), and the surrounding flat terrain is at 200 m (656 ft) above sea level. This gives a hill approximately 5.6 km (3.5 mi) in diameter. Maximum slope angle was 15°. The hill is shown in Figure 1. For solar angle calculations, the hill was arbitrarily located at the location of this conference in Kalispell, MT (48.199316°, -114.315640°). The hill was assumed to be covered by grass. Simulations were done for

September 18th, 2009 from 0600 to 2000 military time in 2 hour increments in clear skies. Input wind speeds of 0, 1.3, and 2.7 m s^{-1} (0, 3, and 6 mph) from 270 degrees (west) were run to demonstrate the interaction of different ambient winds with the diurnal winds. Simulations without diurnal winds were also done for comparison. All reported winds are at the standard meteorological height of 6.1 m (20 feet) above the vegetation.

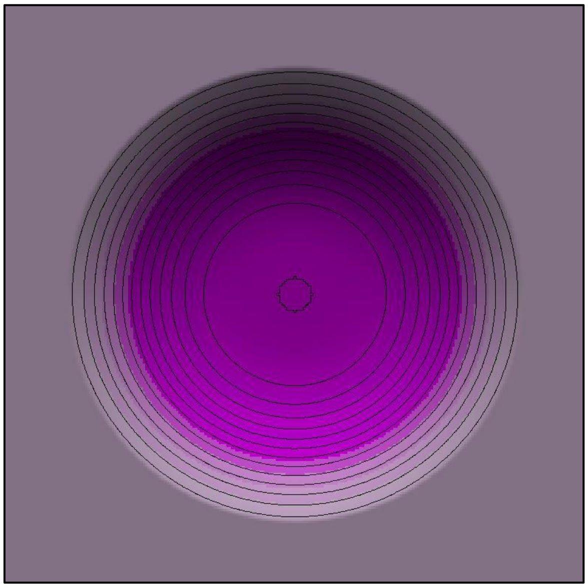


Figure 1. Shaded relief of hill. 30 meter contour lines are shown.

Figure 2 shows simulations without diurnal winds for west ambient flow. Diurnal wind simulations for ambient flow speeds of 0, 1.3, and 2.7 m s^{-1} (0, 3, and 6 mph) are shown in Figure 3, Figure 4, and Figure 5, respectively. Each figure shows simulations for times of 1400 and 2000. Note that the speed scales are different in each figure.

As expected, the wind field in Figure 3 for 0 m s^{-1} (0 mph) ambient winds shows generally up slope wind at 1400 and down slope wind at 2000. Also, the acceleration of the flow up and down the slope can be seen. In the 1400 up slope case, winds on the south slope are somewhat stronger than on the north slope. Figure 4 shows the effect of combining a light 1.3 m s^{-1} (3 mph) west cross flow wind with the diurnal winds. Here, the ambient cross flow and diurnal wind vectors interact to give interesting flow patterns. Where diurnal and cross flow winds act in concert, winds are stronger and when they oppose, winds are lighter. Also, directional changes occur when the winds act at right angles to each other. Figure 5 shows a situation with stronger ambient winds of 2.7 m s^{-1} (6 mph). In this case, diurnal effects are still evident, although their overall effect is less than in Figure 4. This is because the ambient wind is beginning to overpower the diurnal winds. Stronger ambient winds would reduce the impact of the diurnal winds on the overall surface wind pattern even more.

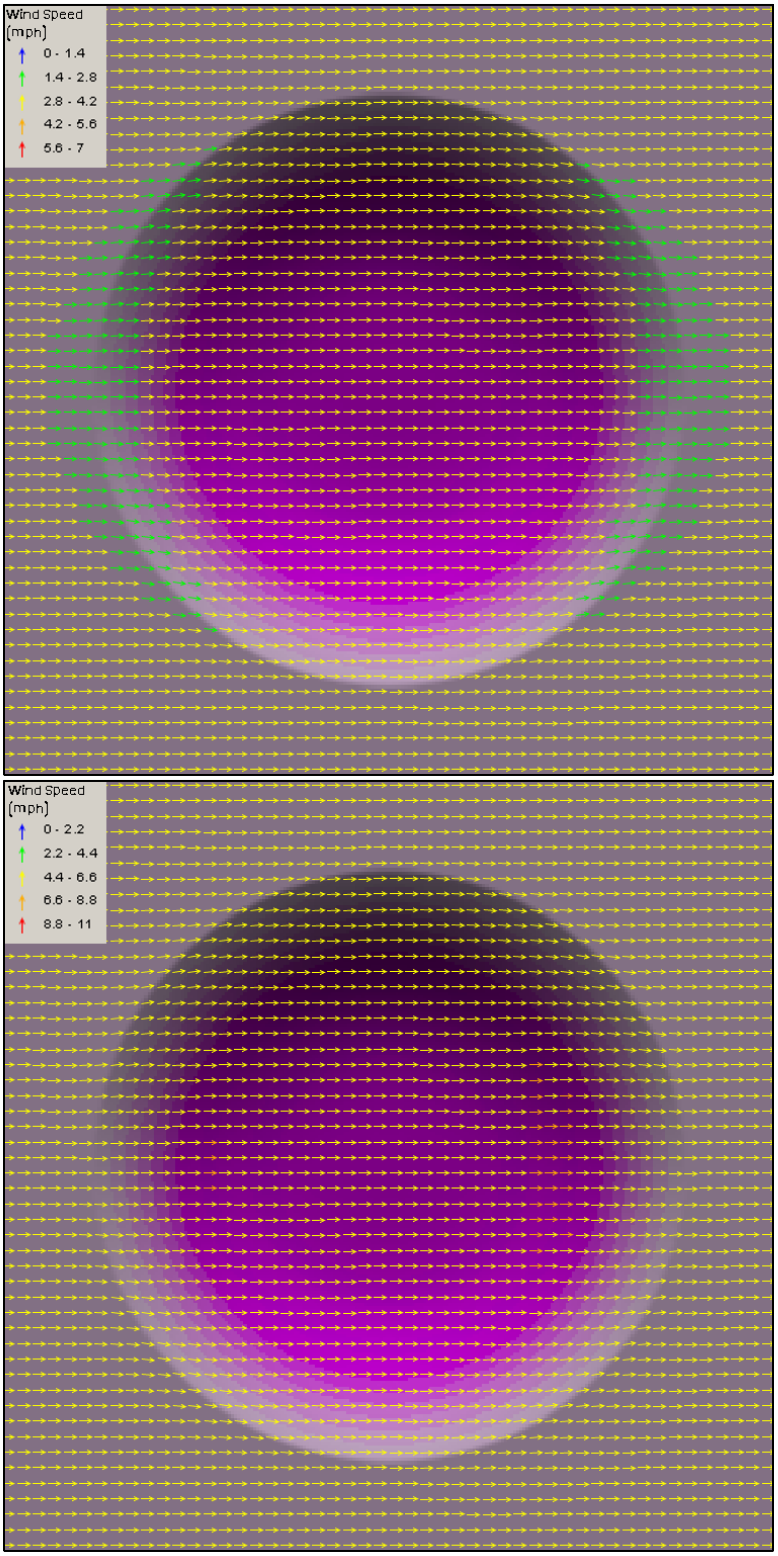


Figure 2. Surface winds for ambient cross flow speeds of 1.3 m s^{-1} (3 mph) (top image) and 2.7 m s^{-1} (6 mph) (bottom image) with no diurnal winds. Note different wind speed legends.

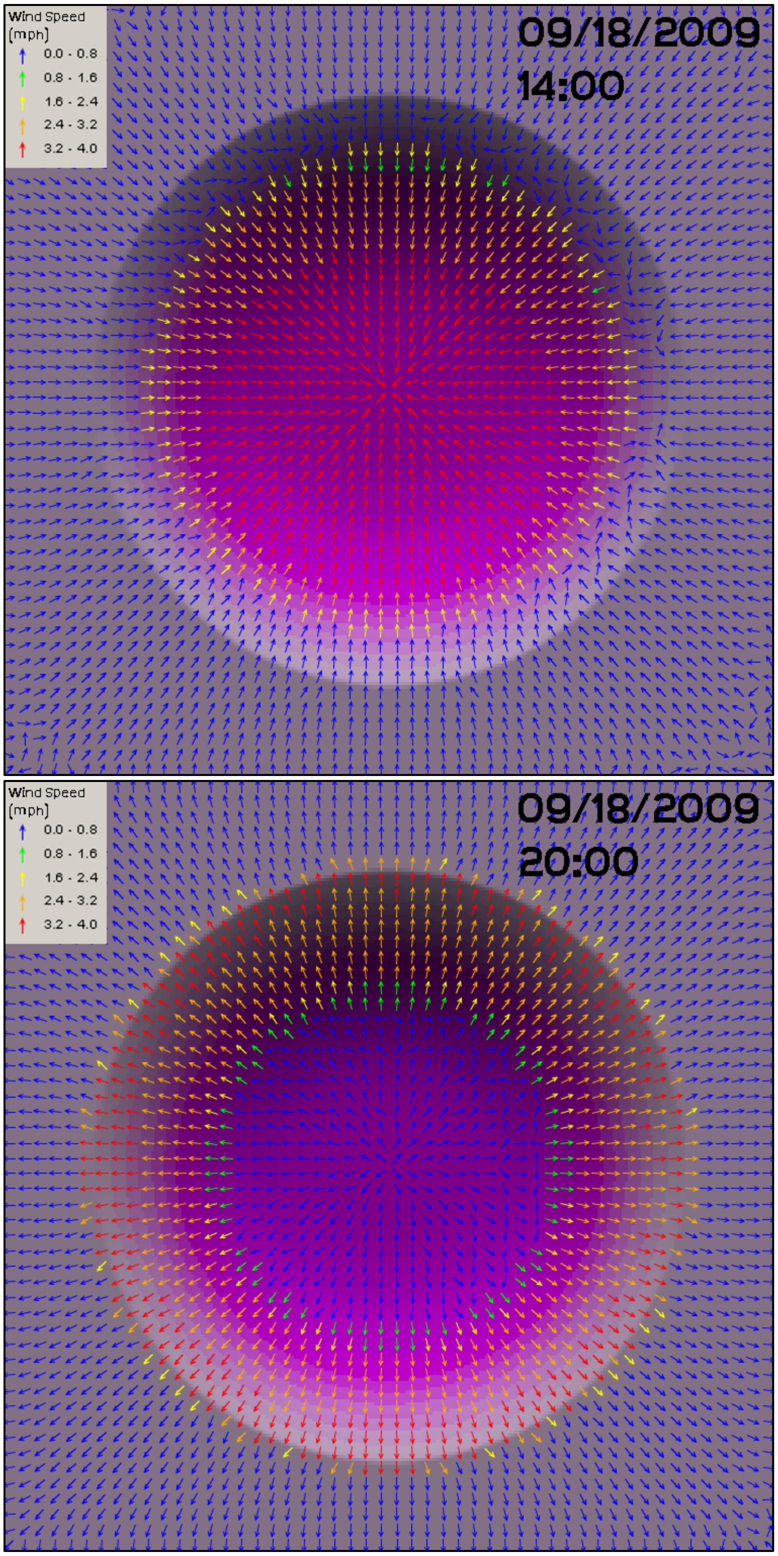


Figure 3. Surface winds for 0 mph ambient cross flow.

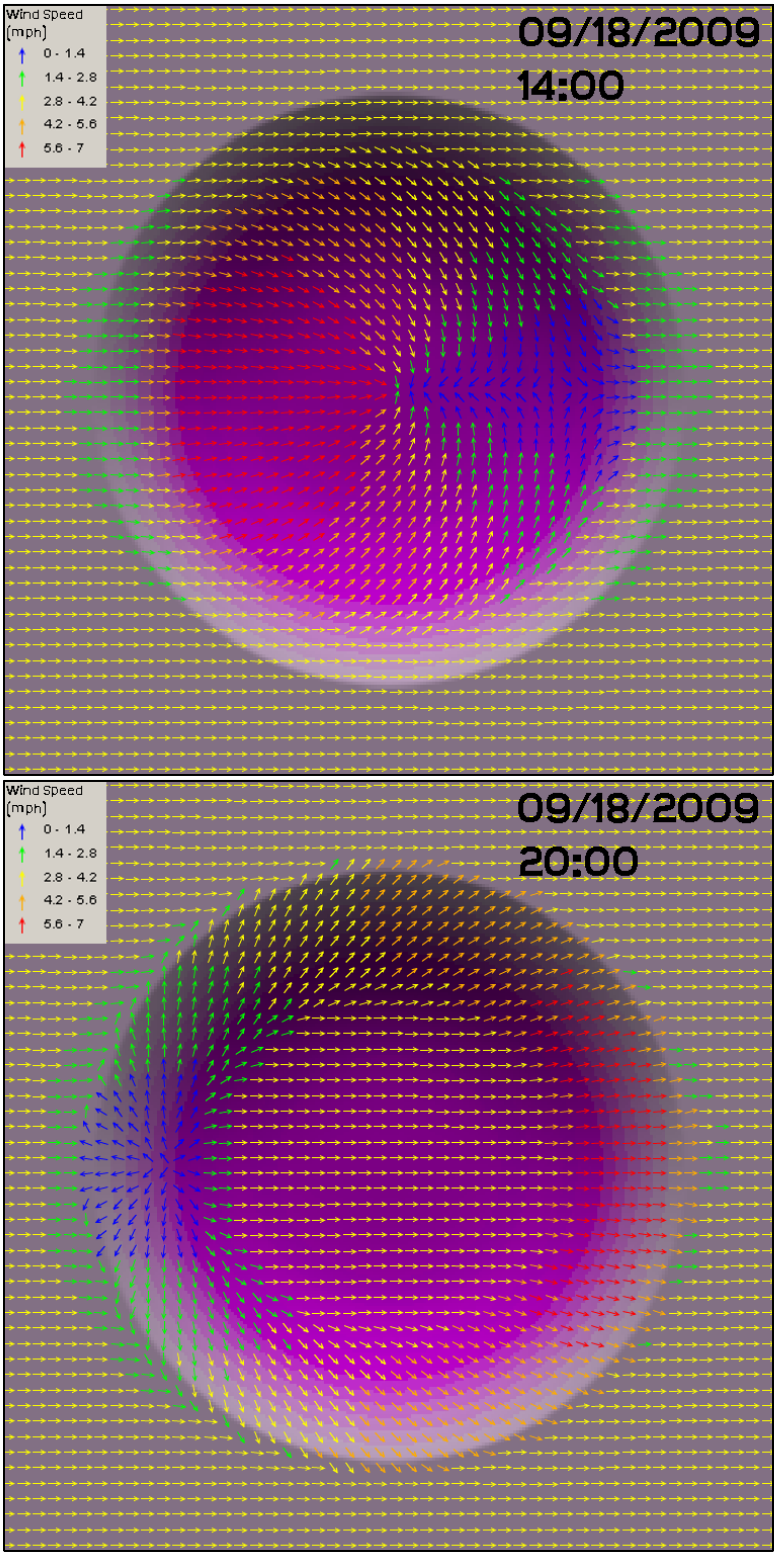


Figure 4. Surface winds for 1.3 m s^{-1} (3 mph) ambient cross flow.

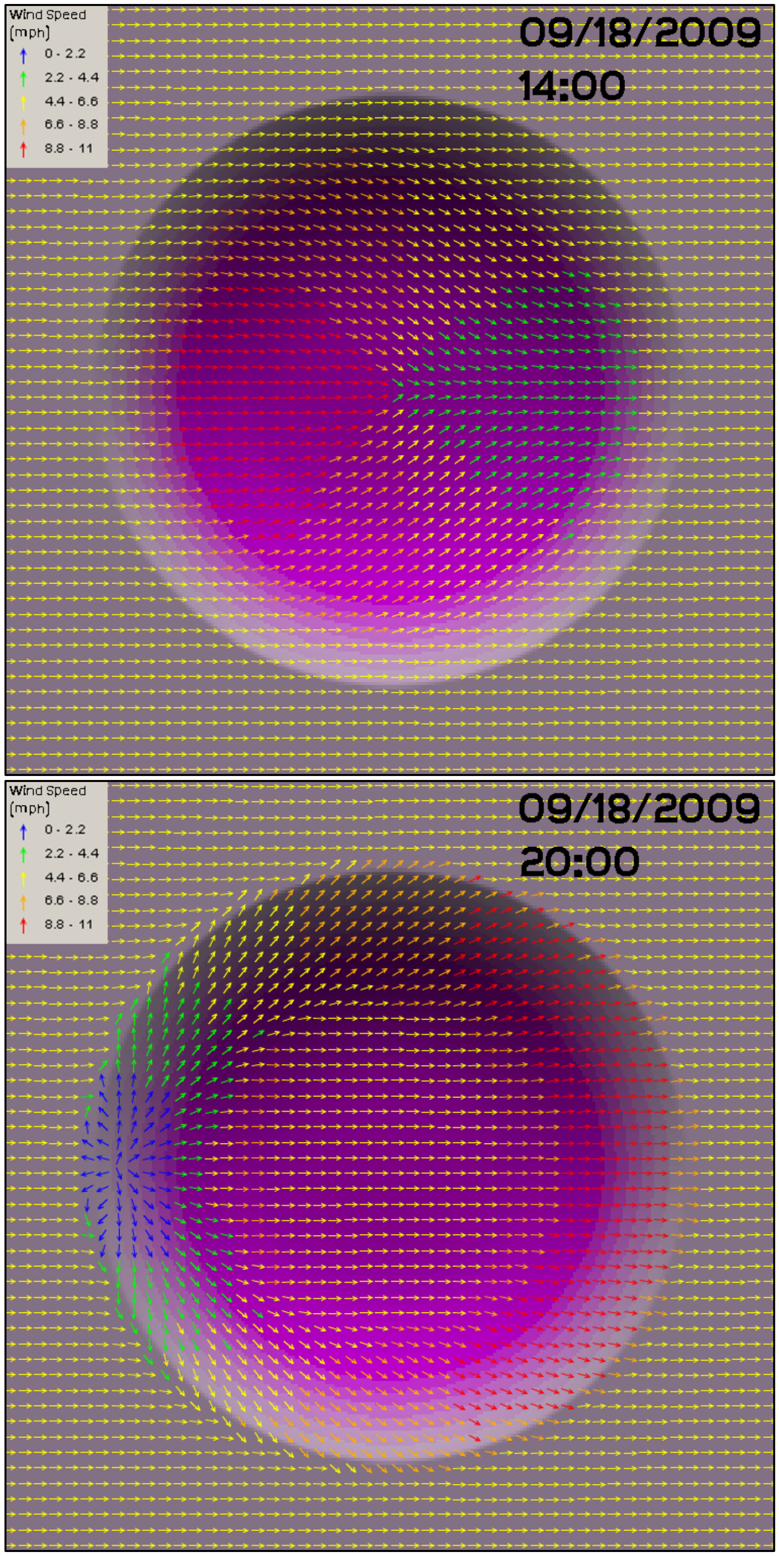


Figure 5. Surface winds for 2.7 m s^{-1} (6 mph) ambient cross flow.

Fire behavior simulations using FARSITE (Finney 1998) and the simulated wind fields were also performed on the hypothetical hill for September 18th from 800-2000. For fire behavior calculations, the hill was assumed to be uniformly covered by grass fuel model 1 (Anderson 1982). Air temperature and relative humidity were set at 27° C (80° F) and 10%, respectively, for the whole day. This was done to reduce the number of factors that change throughout the simulation day to only the wind fields.

Two sets of fire spread simulations were done, corresponding to two different ignition locations. These are shown in Figure 6 and Figure 7. In each figure, comparison of the fire spread is made for three types of wind fields (spatially uniform, WindNinja w/o diurnal wind, and WindNinja w/ diurnal wind) and the three ambient cross flow wind speeds.

Initial inspection of the fire spread shows similar patterns, especially for the same ambient cross flow wind speeds. The commonalities are mainly due to the slope having a relatively dominant effect on the fire spread compared to the fairly low wind speeds. This is exacerbated by the reduction of the winds down to the fire spread model's "mid-flame height". Nonetheless, detailed comparison does show some differences in fire spread due to the incorporation of diurnal winds. An example can be seen in Figure 6 for the 2.7 ms^{-1} (6 mph) case. When comparing the WindNinja runs with and without diurnal winds, on the east side of the hill it is evident that the diurnal wind case showed a retarding effect on fire spread during the daytime up slope winds. Later in the day, down slope winds aided the down slope progression of the fire. Another example is shown in Figure 6 for all cross flow cases, where upslope winds on the south slope increased fire spread up the slope during the daytime.

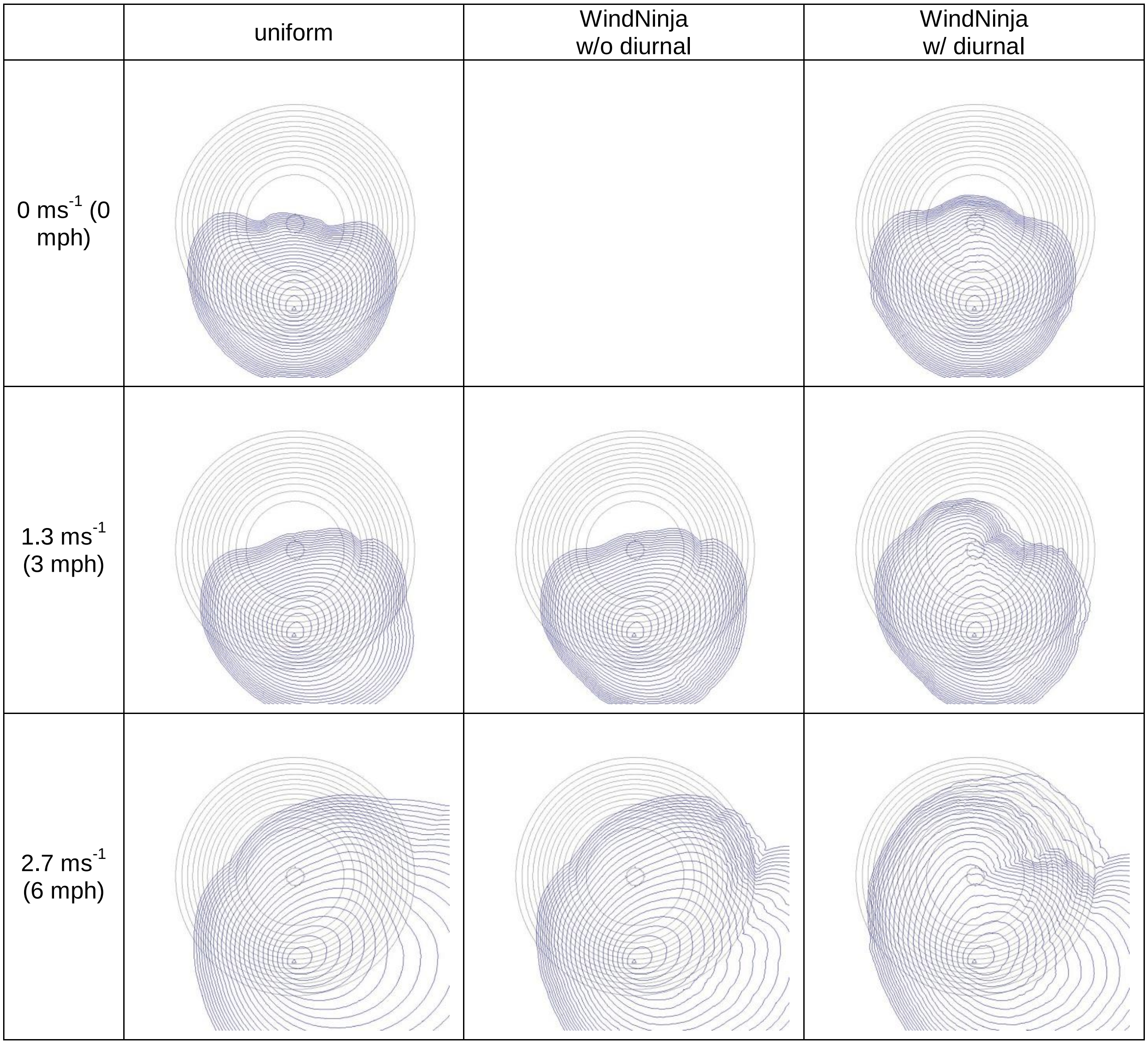


Figure 6. Comparison of fire progression from 0800-2000 on September 18th using different wind fields. Fire isochrons, shown in blue, represent 30 minute spacing. Gray lines are 30 meter elevation contours.

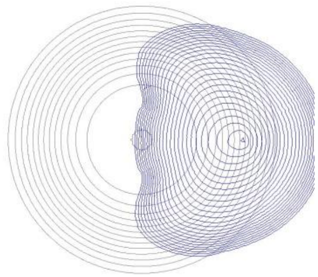
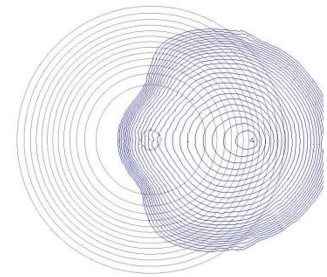
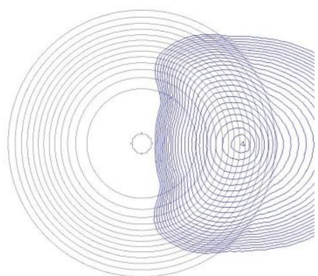
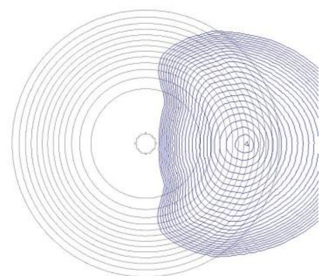
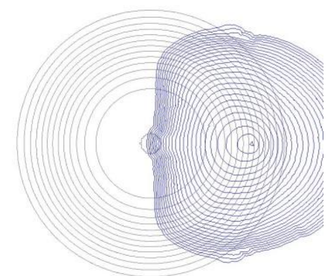
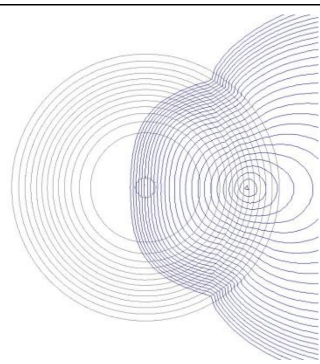
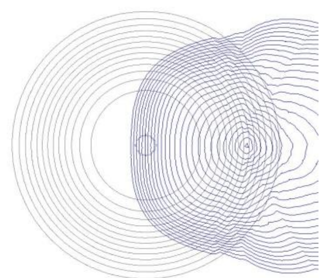
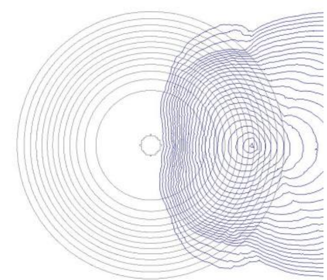
	uniform	WindNinja w/o diurnal	WindNinja w/ diurnal
0 ms^{-1} (0 mph)			
1.3 ms^{-1} (3 mph)			
2.7 ms^{-1} (6 mph)			

Figure 7. Comparison of fire progression from 0800-2000 on September 18th using different wind fields. Fire isochrons, shown in blue, represent 30 minute spacing. Gray lines are 30 meter elevation contours.

5. SUMMARY AND CONCLUSIONS

A diurnal slope wind model added to the WindNinja microscale model has been described. The diurnal model requires few additional inputs and can be run quickly by fire analysts with little training. The model gives qualitatively reasonable results for up slope and down slope winds, although it has not been validated against measured data. Fire simulations for one day over a simple hill showed that the diurnal slope winds have an effect on the fire progression. Simulations in complex terrain and over multiple days are expected to show larger deviations from those without diurnal winds included. Incorporation of the new diurnal model is expected to be a useful tool for fire analysts because fires often burn in relatively calm ambient wind conditions influenced strongly by diurnal slope winds.

6. REFERENCES

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