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Representativeness of wind measurements in fire experiments: Lessons learned from large-eddy simulations in a homogeneous forest

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ABSTRACT

Experimental fires often aim to relate fire behavior to fuel and weather conditions, such as wind speeds. These experiments are typically limited to short durations (~300 s) and small lateral extents (~100 m). Although most studies include measurements of wind velocities, such measurements are often taken at some distance from the fire experiments, and may not represent conditions at the fire location. This disparity may potentially introduce errors of unknown magnitude in empirical models based upon the data collected. At present, little guidance is available regarding how well remote anemometry measurements are actually representative of wind velocities at the fire front. A number of factors may affect this representativeness, including the fire itself (size, spread rate and duration), the reference height for fire wind measurement, the sensors (number and location), the vegetation, and weather conditions (wind speed and atmospheric stability).

In the present study, we use large-eddy simulations of wind flows to compute fire-front wind (at a virtual moving fire line) and measured wind (at anemometer locations) corresponding to hypothetical fire experiments. Replicates of these hypothetical experiments were used to quantify wind measurement representativeness, by computing the errors resulting from the estimation of the fire-front wind by remote anemometers. We then examine the sensitivity of these errors to the factors mentioned above.

We found that the main factors were the size of the experiment, the reference height for wind measurement, the ratio of ambient wind speed to expected spread rate, and the number of sensors. Convective instability and distance between anemometers and fire plots played a minor role in most cases. We propose a simple model to characterize this error as it is influenced by the main factors.

The simple model reproduces and generalizes outcomes reported by an earlier field study and shows a clear picture of the respective role of the factors cited above. It can be used to estimate errors in wind measurement in completed experiments. Practical guidelines are provided to apply this model to the design of future experiments.

1. Introduction

One of the major foci of forest fire research is to relate fire behavior to the surrounding environmental conditions, such as wind characteristics. This is frequently attempted though important fire experiment campaigns (e.g. Taylor et al., 2004; Clements et al., 2007, 2016). Such experimental fires have spatial and temporal scales in the order of tens of meters and few minutes. They provide data that can be used to build empirical models statistically associating fire rate of spread (ROS) and wind velocity in the direction of spread (Sullivan, 2009). This is usually accomplished by fitting curves through scattered data (Sullivan and Knight, 2001; Cruz and Alexander, 2013). A critical assumption in this approach is that mean spread rate correlates to mean wind speed (Cheney and Gould, 1995). However, past studies exhibit wide variability in how well this assumption holds, due to a number of factors, including wind measurement accuracy (Cruz and Alexander, 2013). Indeed, measuring the wind in wind-related phenomena is challenging due

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Nomenclature

Symbols, abbreviations and definitions

$\tilde{E}$	Estimated error, including the impact of sensor location (%)
$\tilde{E}_{fit}$	Model fit of estimated error $\tilde{E}$ (%)
E	Estimated error, as a function of sensor location (%) – Appendix A (in Supplementary material)
h	Vegetation height (m)
L	Fire-experiment plot size (m)
LES	Large-Eddy simulation
N	Number of virtual sensors used to measure wind speed during a hypothetical fire experiment
$\tilde{n}$	Number of spatial and temporal replicates of fire experiments and measurement set-up (used to compute $\tilde{E}$)
n	Number of spatial and temporal fire-experiment replicates
n_m	Number of spatial configurations averaged when the impact of sensor location was included in estimated error
n_P	Number of fire-experiment plots (spatial replicates)
n_T	Number of temporal fire-experiment replicates
ROS	Fire rate of spread ($\mathrm{m\,s^{-1}}$)
U_{40}	Reference wind velocity at $z = 40$ m, used to defined LES
u_f	Fire-front wind ($\mathrm{m\,s^{-1}}$). idealized wind that would have been measured at fire location, without the presence of the fire
$\overline{u_f}$	Time average of the fire-front wind speed u_f over the experiment duration ($\mathrm{m\,s^{-1}}$)
u_m	Measured wind ($\mathrm{m\,s^{-1}}$). wind actually measured by one or several sensors (that are virtual sensor in the present study)
$\overline{u_m}$	Average of the measured wind speeds u_m of a group of N sensors over the experiment duration ($\mathrm{m\,s^{-1}}$)
S_1, S_2, S_3	LES with respectively low, medium and height wind speed under neutral conditions
S_{2c}	LES with medium wind speed and convective instabilities
T	Fire-experiment duration (s)
$\langle w'\theta' \rangle_s$	Surface kinematic heat flux leading to convective instabilities in simulation S2c ($\mathrm{K\,m\,s^{-1}}$)
Δx, Δy	Upwind and crosswind distances from the fire plot (m)
z_{ref}	Reference height for fire and measured wind velocities (m)

to the wind's turbulent nature. This is especially challenging with experimental fires.

Winds cannot generally be measured at fire-front location, as most instruments cannot survive a fire, and it is challenging to take mobile measurements that would follow the fire front. Thus, there is always a departure between the actual wind that influences the fire spread, and the wind speed measured remotely. This departure determines the representativeness of wind measurements, which can be estimated by the numerical quantification of a measurement error (Sullivan and Knight, 2001). This representativeness is often referred to as measurement accuracy (Sullivan and Knight, 2001; Cruz and Alexander, 2013), even if this term may evoke the accuracy of the sensor itself. This first source of departure is amplified by the interactions between the fire plume and the ambient wind, mostly related to buoyancy force that can significantly alter the ambient wind statistics (Trelles and Pagni, 1997; Clements and Seto, 2015; Clements et al., 2016). These fire feedbacks on the local wind field should be accounted for in fire-model formulations. They are beyond the scope of this study and are not included in wind errors, usually estimated without the presence of a fire (Sullivan and Knight, 2001).

The measurement error is associated with the departure between the wind speed that would have been measured at fire location (without fire), referred to as the fire-front wind (u_f) and the measured wind speed at one or several remote locations (u_m). The distances between sensors and fire varies among studies (e.g. between some tens and 700 m in Taylor et al., 2004), but they are typically much greater than the turbulent length scales associated with spatial correlations observed in wind measurements, which are on the order of the canopy height (Finnigan, 2000). Consequently, there is in general no correlation between the time series of u_f and u_m. However, temporal averages of u_f and u_m over the duration of the experiment ($\overline{u_f}$ and $\overline{u_m}$)may be assumed to match if (1) the duration of the experiment is substantially larger than the turbulent time scales and (2) the vegetation structure is uniform enough over the area encompassing the fire plot and the wind-measurements footprint. Similarly, spatial averages of $\overline{u_f}$ and $\overline{u_m}$ over both the fire-front line and the wind-measurement points are likely to match if the fire line is long enough and the anemometers are numerous enough. In the context of the relatively short duration and small spatial extents of typical experiments, the representativeness of mean remote velocities to estimate the mean velocities at the fire is questionable.

Both simulation and field studies have examined aspects of how wind data affects fire predictions. Using a physics-based fire model, Linn et al. (2012) showed that the predicted fire behavior was quite sensitive to small shifts in measured wind time series, suggesting that a high quality of measurements is required to adequately characterize the wind conditions. The authors of Sullivan and Knight (2001) combined horizontal grid layouts of anemometers under a eucalyptus forest and theoretical considerations to investigate the representativeness of remote measurements and showed that estimated errors were in general quite large (~30 % of the mean wind speed). This influential paper showed that representativeness increases with fire front size and the number of anemometers, and led to useful guidelines for designing fire experiments (e.g. Taylor et al., 2004). Several other factors affect turbulent length and time scales, such as height in canopy, wind intensity and atmospheric instability (Finnigan, 2000) and are thus likely to affect wind measurement representativeness. Their respective roles have not been clarified to date. Among these factors, the role of the measurement height especially needs clarification, since the reference height for wind data, z_{ref}, varies greatly among fire models (e.g. in McArthur, 1967; Forestry Canada Fire Danger Group, 1992; Rothermel, 1972; Albini and Baughman, 1979; Andrews, 2012).

In the present study, we employed a modeling approach, using HIGRAD/FIRETEC (Pimont et al., 2009) to compute Large-Eddy Simulations (LES) of wind flows over a typical fire-prone canopy in various weather conditions of fire experiments. The model is a fully-coupled modeling framework linking an atmospheric code (HIGRAD) and a fire code (FIRETEC). We used the three-dimensional simulated wind fields to estimate the magnitude of the error between fire-front ($\overline{u_f}$) and measured ($\overline{u_m}$)winds. Errors were estimated from a large number of spatial and temporal replicates of hypothetical fire experiments and wind-measurement set-up. We analyzed and discussed the sensitivity of representativeness to fire-experiment characteristics (size, duration, rate of spread), reference height, weather conditions (wind speed, atmospheric stability) and wind-measurement parameters (location and number of sensors). We conclude with a simple error model for wind estimation that can be applied to completed experiments. A series