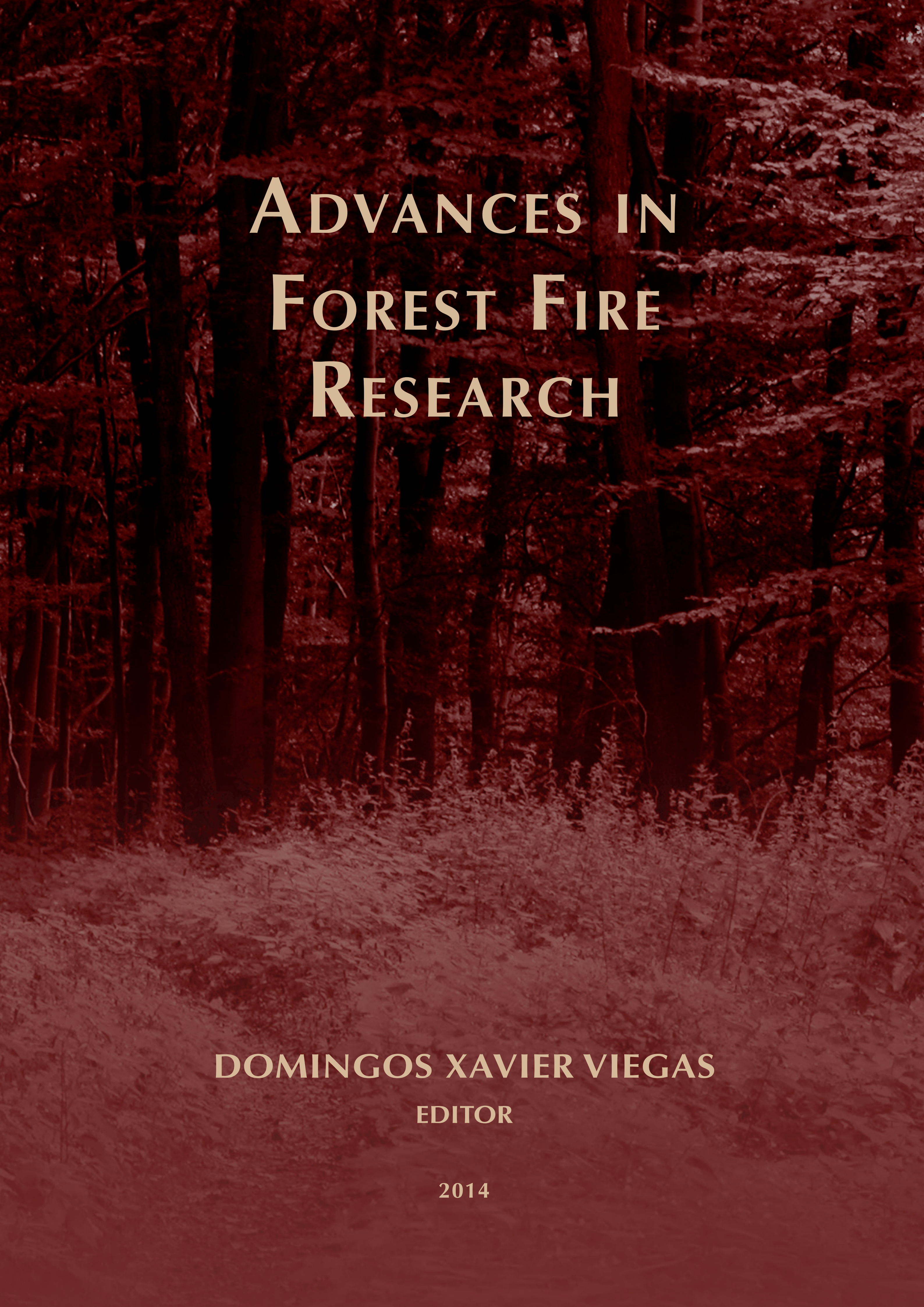

ADVANCES IN FOREST FIRE RESEARCH

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FIRETEC evaluation against the FireFlux experiment: preliminary results

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Abstract

Local dynamic or thermodynamic variables that are the primary time and space dependent variables predicted by the FIRETEC physics-based model of fire behaviour, including gas velocity and gas temperature, have not been tested against experimental measurements to date. In the present study, we attempt to reproduce the FireFlux experiment with the FIRETEC model and we compare the predicted time evolution of wind velocity components and temperatures above the fire to data measured on a tower up to 43 meters above ground level. Given the complex and somewhat uncertain wind and ignition scenario that cannot be exactly reproduced by the model simulation, FIRETEC captured well the timing and magnitude of downdrafts, updrafts and temperature variations observed during the experiment when the fire plume crossed the measurement tower. The drawbacks of the experimental measurements and the influence of ambient wind fluctuations that cannot all be captured by the model do not allow conclusive comparisons regarding turbulent statistics and fluxes during the fire period.

Keywords*: grassland, fire plume, temperature, velocity, model testing*

1. Introduction

FIRETEC is a three-dimensional coupled fire-atmosphere model that allows the simulation of fire spread in natural conditions at a high spatial resolution (one meter) over areas typically 10 to 100 ha. Earlier fire behaviour simulation studies of the physics-based FIRETEC model have provided reasonable results with respect to qualitative and some quantitative observations of global aspects of wildfire behaviour in the field. Previous evaluations considered fire spread in grasslands (Linn and Cunningham 2005), interactions between two fires (Dupuy *et al*. 2011), crown fire behaviour (Linn *et al*. 2012), fuel moisture effect on the rate of spread (Marino *et al*. 2012), or fire shapes as influenced by the combination of wind and terrain slope (Pimont *et al*. 2012). However, local dynamic or thermodynamic variables that are the primary time and space dependent variables predicted by FIRETEC, including gas velocity and gas temperature, have not been tested against experimental data. In fact, only turbulent wind profiles over tree canopies in absence of a fire have specifically been tested to date (Pimont *et al*. 2009).

The FireFlux experiment has already been used to assess the performance of coupled fire-atmosphere models (Fillipi *et al*. 2013, Kochanski *et al*. 2013). The above models are essentially designed to address lower spatial resolution and larger domains than FIRETEC and fire-atmosphere coupling refers to coupling between the atmospheric flow and a fire spread equation, whereas FIRETEC couples the atmosphere with a combustion model. In the present study, we attempt to reproduce the FireFlux experiment (Clements *et al*. 2007, 2008, Clements 2010) with the FIRETEC model. The reader may refer to earlier papers (e.g. Dupuy *et al*. 2011, Pimont *et al*. 2012) for a description of the model.

In the present study, we compare the predicted time evolution of wind velocity components and temperatures above the fire to data measured on a tower up to 43 meters above ground level (AGL). We quickly address the comparison of turbulent statistics and fluxes during the fire period.

2. The FireFlux experiment

The FireFlux experiment was conducted on 23 February 2006 and is described in detail by Clements *et al*. (2007). The atmosphere was neutral except in the first tens of meter. The experimental burn was conducted in a tall grass over a plot approximately 800 m long in the south direction (x-axis) and 400 m wide in the east direction (y-axis). The plot was surrounded by blocks of forested areas dominated by Chinese tallow trees of a maximum height 12-13 m. The experiment was designed to measure the winds and temperatures over the vertical direction as the plume and the fire passed two instrumented towers. A 43 m height instrumented tower (main tower, MT) and a 10 m height tower (short tower, ST) located 300 m downwind of the MT were equipped with three-dimensional sonic anemometers and thermocouple probes. In the current paper, we will focus on measurements at the MT. ST data have only been used together with MT data for adjustment of the wind scenario. The three-components of velocity were measured by the sonic anemometers at 2, 10, 28 and 43 m above ground level (AGL) at MT and 2 and 10 m AGL at ST. These data were recorded at 20 Hz and post-processed to produce valid data files (1 Hz) in earlier analysis. Temperatures were measured by a set of fine-wire thermocouple probes at 1 Hz from 2 to 43 m AGL, we will use only those probes that are located at 2, 10, 28 and 43 m AGL. The sonic anemometers measure virtual temperature, but they could not measure temperatures above 50°C. Temperature recordings readily show that these sensors underestimated the temperatures measured by thermocouple probes, especially at the lowest levels. On the other hand, thermocouple probes were not at the same position as sonic anemometers except at 2 m AGL level. That prevents their use for computation of turbulent correlation between temperature and velocity components (time shift in signals) at all levels.

Fire was ignited by two teams walking respectively to the west (actually 280°) and to the east (100°) direction from a point located in the central part of the plot, at approximately 120 m north of the MT. The timing of fire ignition was recorded for the eastern branch of the ignition line thanks to a GPS located with the ignition crew member. We used these data to build the simulation scenario of the ignition by FIRETEC. It was assumed that the western part was ignited at the same speed as the eastern branch. The exact MT position was known, the position of the ignition point was known within +/- 10 m. Fire spread and fire line shape were difficult to observe and were not well documented. According to temperature data recorded at lowest levels, fire reached the MT at 12:46:40, and according to photographs ignition started at 12:43:36 (+/-6 s) in the data logger clock time. From videos and photographs, the spread of the fire head was about 1.2 m/s when fire approached the tower.

Wind measured at the MT since 12:00 prior to fire ignition indicate that the mean wind speed was about 6 m/s and the mean wind direction was 11°. Wind data also show that wind speed decreased to 3.5 m/s and wind direction changed to North-East (45°) just before the ignition time. These values were observed for 30-40 s after ignition and then wind speed increased again and wind direction changed to the North roughly after about 1 min from ignition time. Later on, the ambient wind at the MT was modified by the fire and the plume, and thus is basically unknown.

3. Simulation setup

The simulation domain was 1200 m long (x-axis), 600 m wide (y-axis) and 615 m high. The actual position of the MT in this domain was (x=636 m, y= 330 m). The computational mesh is orthogonal and stretched over the vertical direction. Cell size was 2 x 2 x 1.5 m at ground level. Figure 1 shows a map of the vegetation types that was produced from an aerial image of the area. Tree canopy was represented by a homogeneous layer of 10 m height and a constant plant area density (note that those deciduous trees were leafed out at the season of the burn). The rest of the area is covered by tall grass (fuel) and some areas of cut grass.

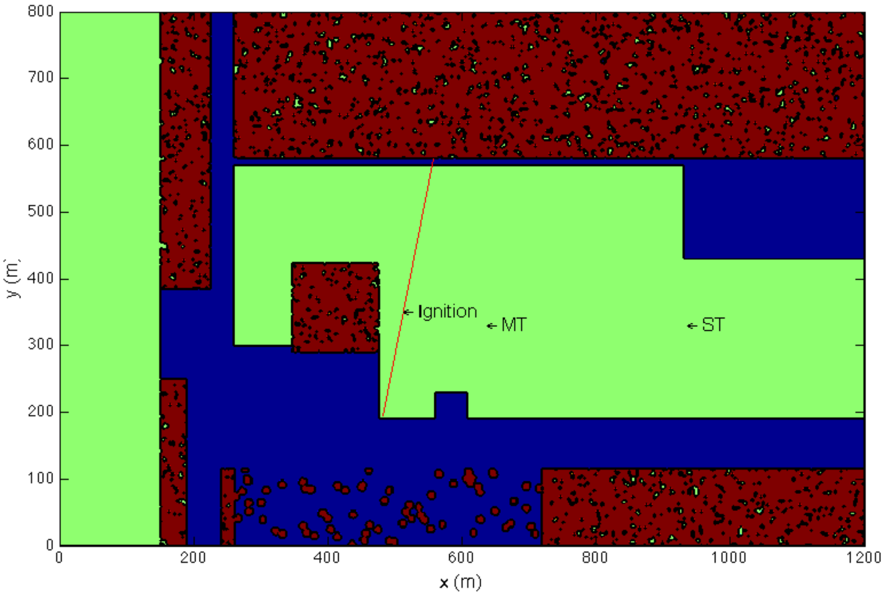

Figure 1. Simulation domain and vegetation map (Red : trees; Green : tall grass; Blue : cut grass)

A turbulent wind field was pre-computed using the same simulation domain dimensions, but the area was covered by a 600 x 600 m strip of tree canopy and two strips of tall grass upwind and downwind of the tree strip. This pre-computation used cyclic boundary conditions and a large-scale pressure gradient force method to allow the development of realistic turbulent structures due to vegetation roughness. In this method, a target wind is specified at some height where drag effects are minor (here 43 m AGL). Then the pre-computed wind field was used to set the initial and the boundary conditions for the computation of fire spread over the map shown in Figure 1. In this simulation, ignition started 300 s after run start to allow the wind field to adjust to the drag effects of the actual map of vegetation. In particular, the block of trees located just upwind of the ignition line influenced the wind field in the area of interest (between ignition line and MT). We adjusted the initial wind of the pre-computation and the (unknown) plant area index (PAI) of the tree blocks to get mean wind speed values closed to the observed ones at 10 m AGL at both the MT and the ST (respectively 4.9 and 5.7 m/s). That led us to use a 7 m/s wind speed and 11° wind direction at 43 AGL in the pre-computation and a PAI of 0.2 for the tree canopy with a drag coefficient set to 0.15. Fuel parameters were set following estimates reported in Clements *et al*. (2007) and ignition reproduced the process described in section 2. Fuel and ignition parameters are reported in Table 1.

Because fuel was removed 5 m around the tower base, we ran two fire simulations, one with no fuel clearing and one with fuel clearing (residual fuel load: 0.05 kg/m^2) in a square of 14 m side centred on the tower location. In fact, fuel clearing in the simulation was not operated at the actual tower location, but at two locations among points that were reached by the head fire within the observed timing. This is explained in the next section.

Table 1. Fuel (tall grass and live shrubs) and ignition parameters of the simulation

Fuel height (m)	1.5	Length of ignition western branch (m)	155
Fuel load (kg/m^2)	1.08	Duration of ignition western branch (s)	138
Dead fuel (% load and cover)	96	Length of ignition eastern branch (m)	237
Dead fuel moisture content (%)	9	Duration of ignition eastern branch (s)	205
Live fuel moisture content (%)	200	x, y position of ignition start (m)	513, 350

4. Results and discussion

4.1. Ambient wind adjustment

The experimental wind profile at MT, determined from recordings prior to fire ignition, was not perfectly predicted by the model at that location. To get the observed value at 10 m AGL, the mean predicted wind speed was close to 7 m/s at 43 m AGL at MT (the same as in the pre-computation), whereas the observed value was 6 m/s. We suspect that the model overestimates the influence of trees on the mean wind profile downwind of tree canopy since we got a profile close to the measured wind profile some tens of meters downwind of the MT.

4.2. Fire spread

Figure 2 shows the simulated fire front 60 s, 120 s and 190 s after ignition start. According to temperatures predicted at 2 m height, fire reached the x-position of the MT (636 m) within 185 and 195 s after ignition for points located between 340 and 370 m in y-direction, thus exactly the experimental timing. The actual y-position of the MT (330 m) was reached with ~ 10 s delay in the simulation. Owing to the uncertainty on the actual position and timing of the ignition line building, we did not expect a better result. In fact we must consider that within a few tens of seconds, this timing was obtained just by chance. The strong change in wind speed and direction during the initial development of the fire line cannot be rendered by the model simulation and certainly affected the fire line spread and shape and when plume and fire reached the MT just 2-3 minutes later. This change is likely due to large-scale atmospheric structures that cannot be captured with the current technique used to compute the ambient wind.

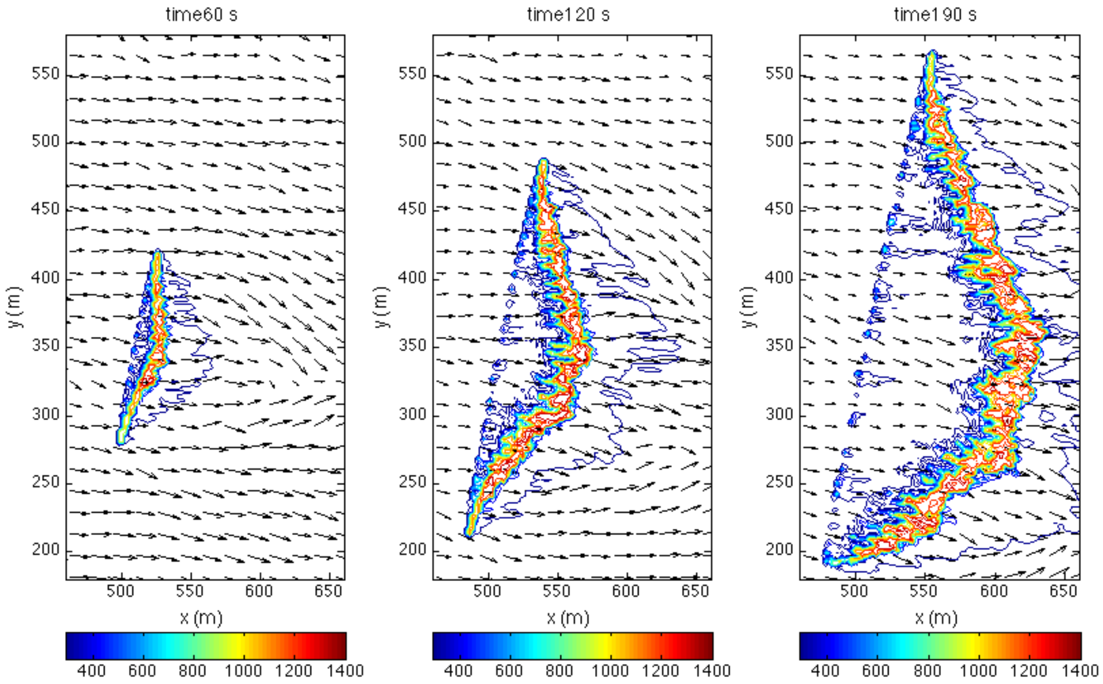

Figure 2. Fields of gas temperature (0.75 m AGL) and horizontal wind (10 m AGL) simulated with FIRETEC, 60 s, 120 s and 190 s (arrival of fire head at x=636 m) after the ignition

In the following, we will focus on those points comprised between y=340 m and y=370 m where fire arrived at x-position of the MT (636 m) in a timing close to the experimental one. In all time series plots of the variables, time zero corresponds to the ignition start time and fire reached the MT at ~ 190 s. Predicted time series are all shown together with the experimental one.

4.3. Horizontal velocity

We will only report results for the u-component of velocity (x-axis), which is the major component of horizontal wind speed (mean angle with North is only 11°) and drives the plume along the x-axis. Figure 3 shows 1 Hz time series of the u-component of velocity at y=340 m and y=370, and at 10, 28 and 43 m AGL. As expected (section 4.1), the mean wind speed is over-predicted at 43 m AGL and to a lesser extent at 28 m AGL, but also at 10 m AGL. In fact, variations in the measured wind are much higher than variations in the computed velocity. This was also observed prior to fire arrival (variance of predicted and measured velocities) and confirms we cannot capture all ambient wind fluctuations. The comparison between predicted and measured horizontal velocities is thus delicate since we cannot separate the largest variations due to the ambient wind flow structures (that cannot be rendered by the model) from the impact of the fire in the experimental data. At least a wind measurement not influenced by the fire should be used to do so. Nevertheless, experimental data exhibit two minimum values at all heights (approaching zero at 10 m AGL), prior to plume arrival, and then an increase of the wind when the plume crosses the MT. The model captures the increase in wind speed as the plume passes, but not the strong wind decay prior to plume arrival.

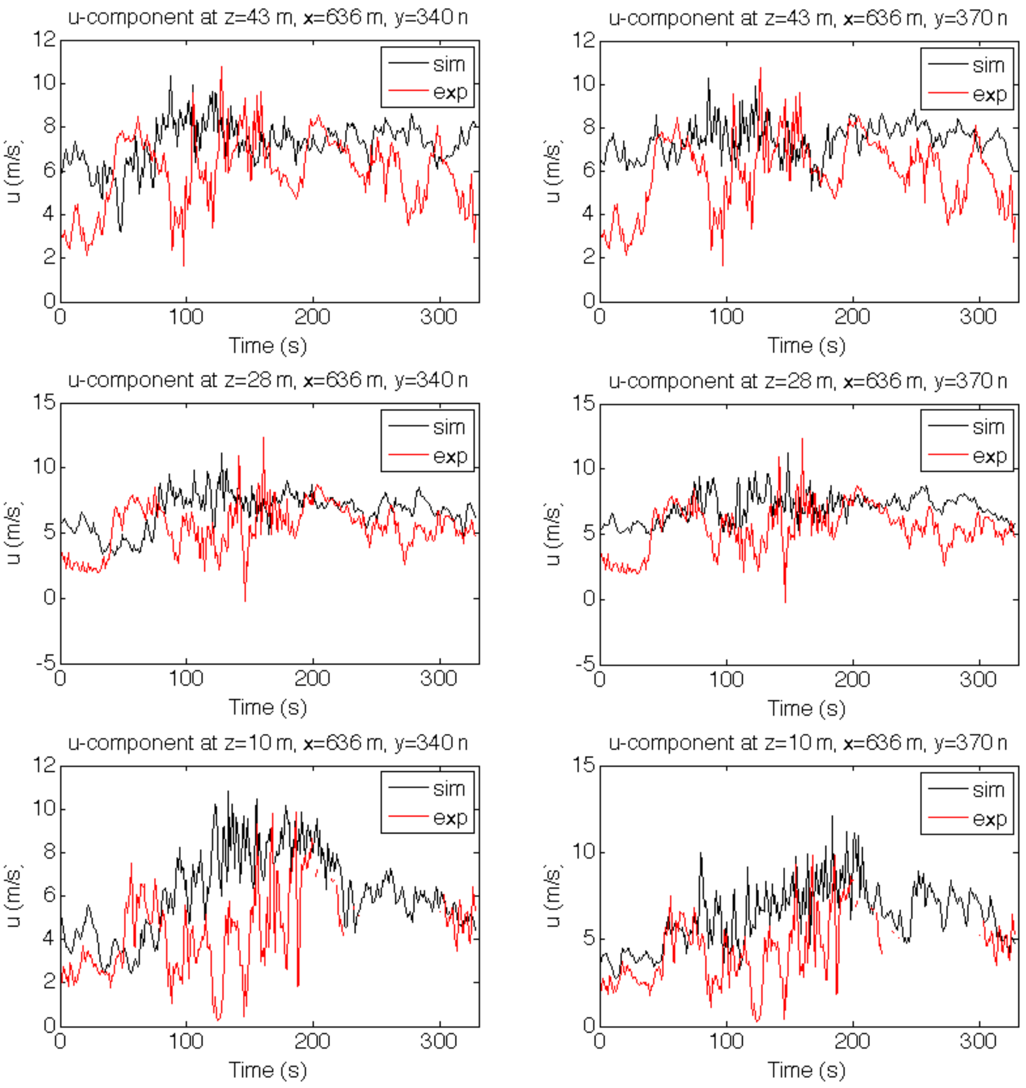

Figure 3. u-component of velocity versus time (1 Hz) at 10, 28, and 43 m AGL, at two points (sim) and at MT position (exp)

4.4. Vertical velocity

Over a flat terrain and in near neutral conditions, the ambient flow should have a small effect on vertical velocity as compared to the fire, which is a high source of buoyancy. In other words, comparisons of the model predictions to measured w-component of velocity should be meaningful for the model assessment. Figure 4 shows 1 Hz time series of the w-component of velocity (vertical velocity) at six points together with the experimental measurement, at 28 m AGL. The predicted and experimental patterns are very similar, in timing and in magnitude. In particular, the model renders the increase in vertical velocity peak values as the plume crosses the points and the downdraft observed just after the plume passed the tower location. Consistency between predicted and measured w-velocity patterns is confirmed at other heights (shown for two points in Figure 5). Figure 6 shows 10 s-averaged data at the six points between 340 and 370 m. It is easier to depict the magnitude of velocity and worth noting that variations among simulated points are important.

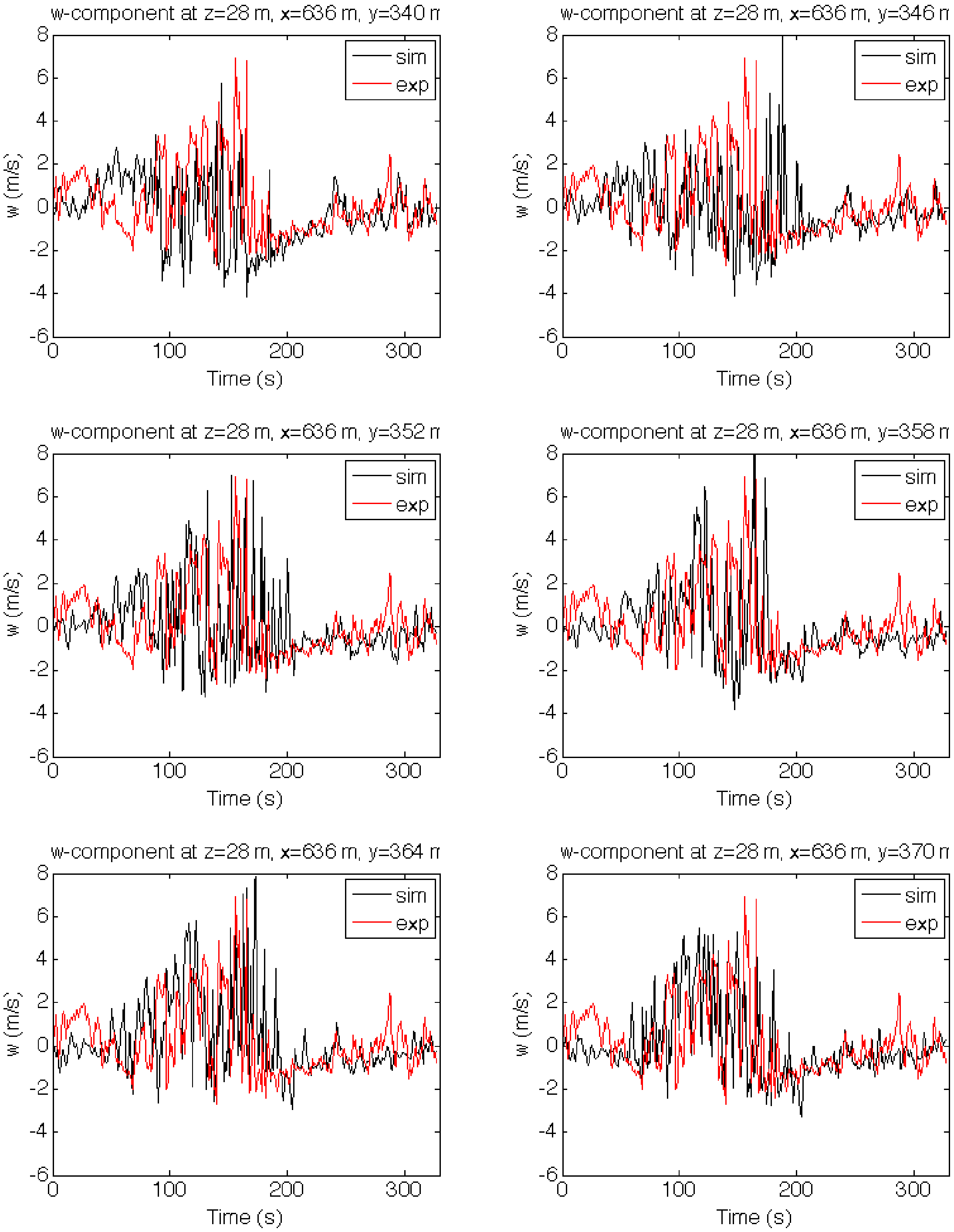

Figure 4. w-component of velocity versus time (1 Hz) at 28 m AGL, at six points (sim) and at MT (exp)

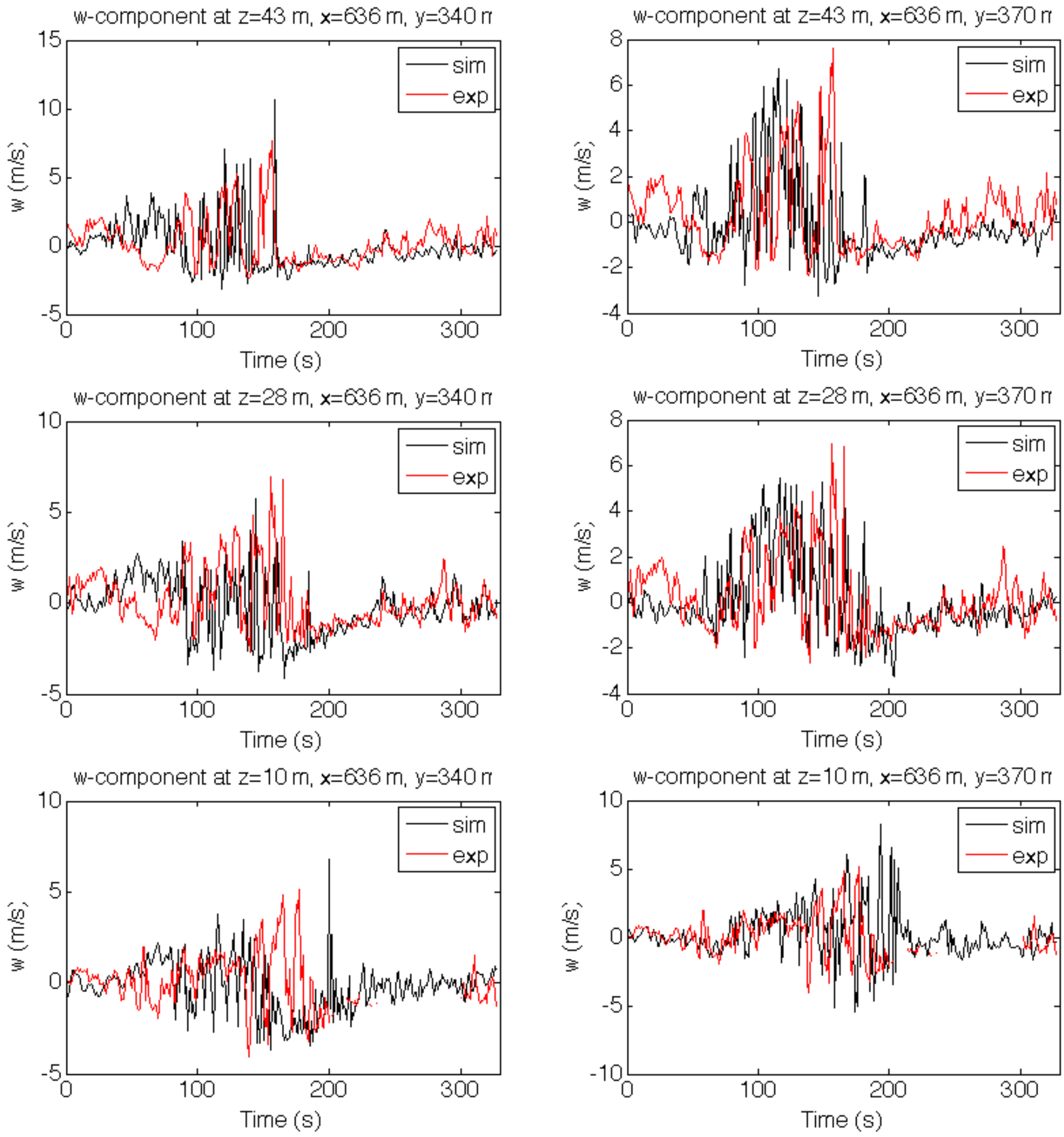

Figure 5. w-component of velocity versus time (1 Hz) at 10, 28, and 43 m AGL, at two points (sim) and at MT position (exp)

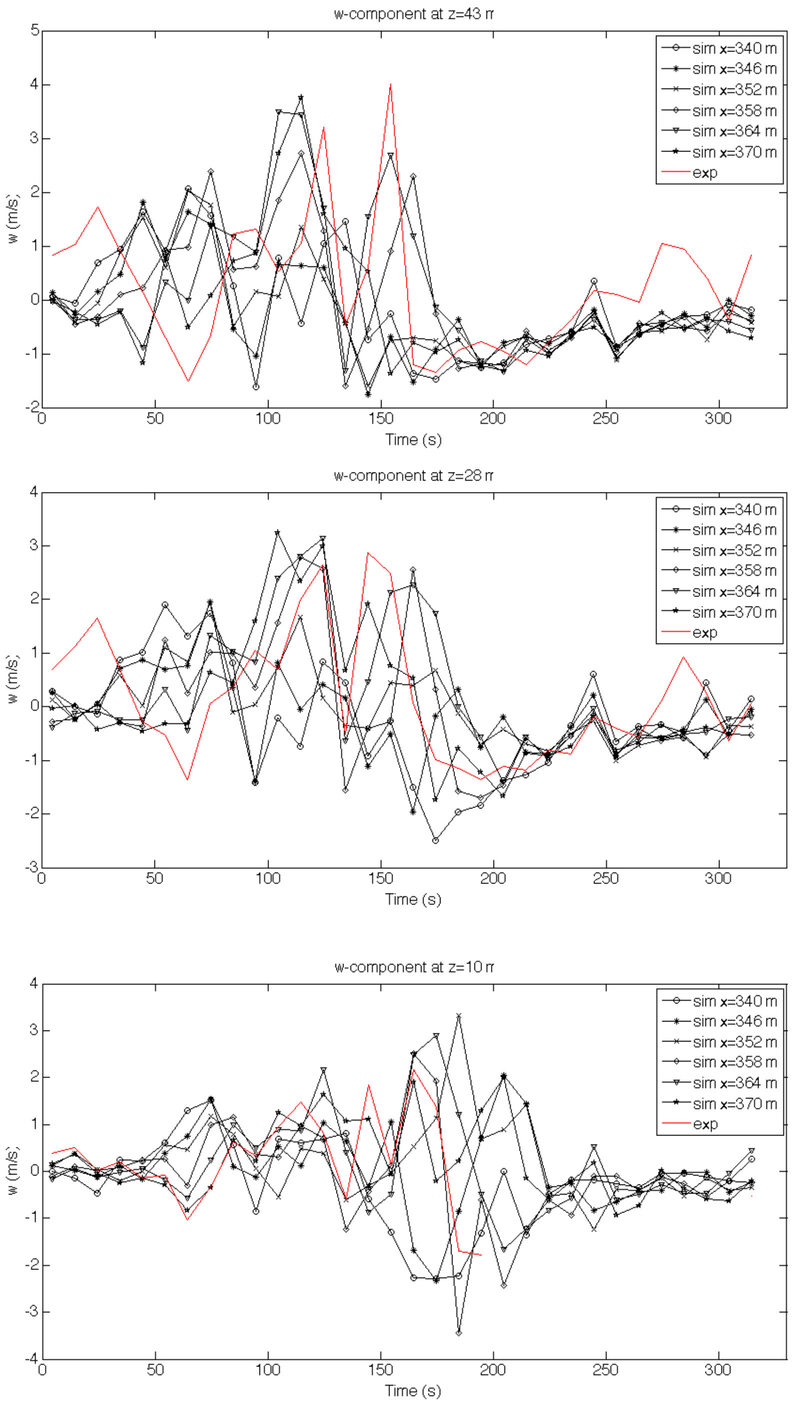

Figure 6. w-component of velocity versus time (10s-averaged data) at 10, 28, and 43 m AGL, at six points (sim) and at MT position (exp)

4.5. Temperatures

Plots of 1 Hz temperature time series at 10, 28 and 43 m AGL all show the same general pattern, but also important variations among points between y=340 and y=370 m (not shown). Figure 7 shows those time series of temperature at two points and three heights AGL (10, 28, 43 m). The plume impinges the upper levels of the tower earlier than in the experiment, typically 40-50 s earlier at 43 m AGL and 20-30 s earlier at 28 m AGL. This results in higher predicted temperatures than observed when the plume starts to cross the tower. That can be easily seen for the six points between 340 and

370 m on 10-s average plots of temperature (Figure 8). We assume that these differences are essentially due to differences in horizontal wind speed described above and to the initial wind change observed in the experiment. Higher wind speeds imply that heat is advected faster. The wind change in both speed and direction in the experiment is likely to have delayed plume impingement on the tower. It is worth noting from Figure 8 that the observed peak value of temperature at the three heights is in the range of predicted values, which however vary a lot among the different points.

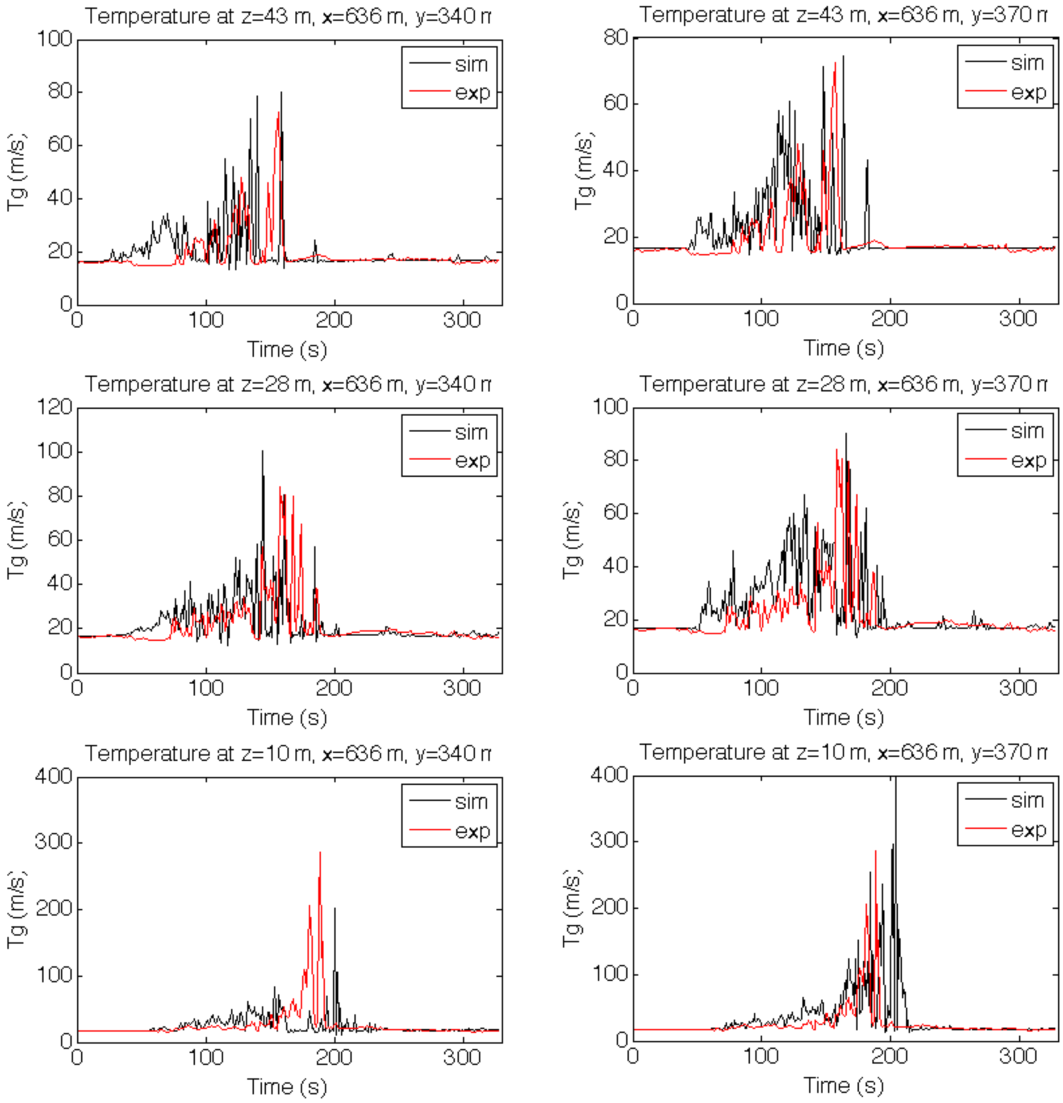

Figure 7. Temperature versus time (1 Hz) at 10, 28, and 43 m AGL, at two points (sim) and at MT position (exp)

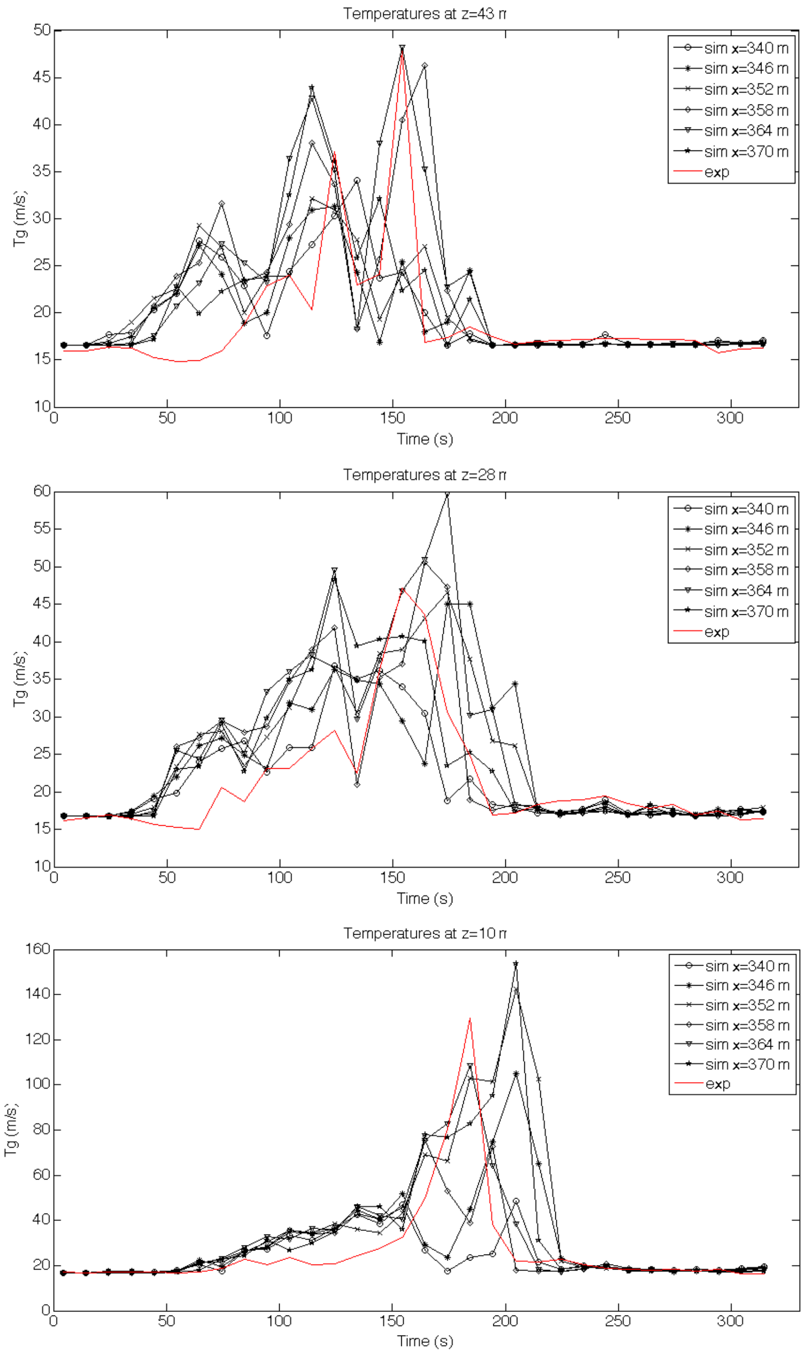

Figure 8. Temperature versus time (10s-averaged data) at 10, 28, and 43 m AGL, at six points (sim) and at MT position (exp)

4.6. Influence of fuel clearing

In a second simulation, fuel was cleared at y=340 m and y=370 m. Clearing had little effect on velocity and temperature patterns at the upper levels. We noticed some small changes in the temperature peaks at 10 m (not shown). This was expected since heat is advected faster in the horizontal than in the vertical direction (two times faster in order of magnitude in the simulation). In contrast, changes in temperature were very large at 2 m height. Figure 9 shows that peak temperatures were strongly reduced when clearing was applied and that predicted temperature levels with clearing match the observed values. Clearing also reduced the peak values of vertical velocity reached when the fire crosses the base of the tower (not shown).

4.7. Turbulent statistics

Turbulent statistics of atmospheric flows are meaningful when computed over time samples large enough to consider that variables are stationary. During the plume and fire passage, all variables measured at a fixed point are clearly unsteady. In addition, in the present experiment, measurements were taken at a position that was influenced by the initial development of the fire since the duration of ignition and the time to reach the MT were similar. Only point probes "attached" to a steady fire or more realistically 1D or 2D fields of data measurements, would be able to provide such statistics. This is of course a great challenge to perform such measurements.

Statistics may be computed over some reference time period with the purpose of model-experiment comparison only. Unfortunately, both the current technique of ambient flow modelling used by FIRETEC and the drawbacks of the temperature measurements strongly limited the possibility to perform such comparisons. As we mentioned, ambient wind variations are likely to influence the horizontal components of wind in the plume and as such, should influence their variance and co-variance.

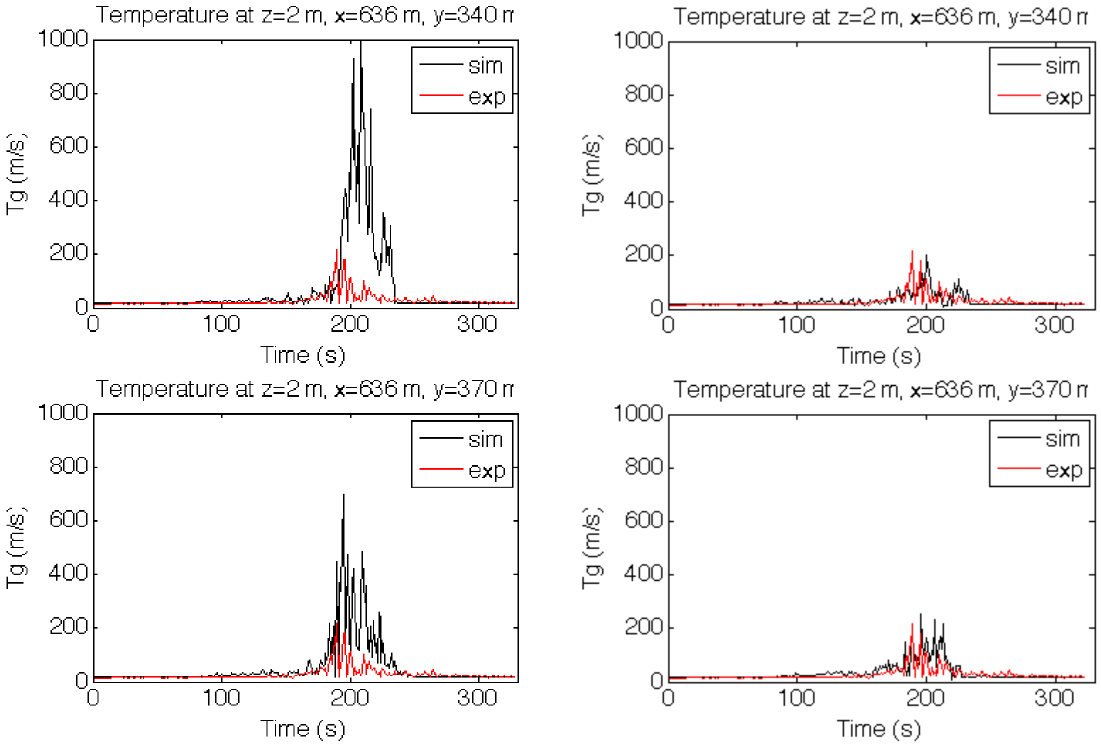

Figure 9. Temperature versus time (1 Hz) at 2 m AGL, at two points (sim) and at MT position (exp). Left : no fuel clearing; right : fuel clearing at point location

We readily found in the pre-fire period that the observed variances of u and v components of velocity were underestimated by the model, because we only capture those variations that are due to the vegetation roughness in the simulated domain we used. Besides, sonic temperatures were underestimated by the sonic anemometers, which compromises the calculation of the vertical sensible heat flux or the vertical buoyancy (e.g. basically the correlation of the vertical velocity and the temperature).

To support the above assertions, we computed one minute moving averages of velocity component variances and co-variances and the covariance of vertical velocity and temperature (w't') on 5 Hz data. We tracked the extrema of these statistics during the fire period (0 to 5 min after ignition). Those statistics were computed for the 16 points of the simulation located between y=340 and 370 m, and for the experimental data, at 10, 28 and 43 m AGL. As expected, the model underestimated the observed peak variance of horizontal velocity (u'^2, v'^2) and the magnitude of the (negative) peak vertical momentum flux (u'w'). The variance of the vertical velocity (w'^2) from the observations was similar to the model. The experimental w't' correlations (or the sensible heat flux) were clearly below the model predictions and it decreased with decreasing height AGL, whereas it increased in the model predictions.

5. Conclusion

The current work is the first assessment of temperature and velocity predictions by FIRETEC against data measured in a plume developed from a spreading fire in natural conditions. The updrafts and downdrafts observed in vertical velocity measurements are particularly well captured. Temperature magnitude at different heights is also well captured. This is particularly important because these two variables are mostly determined by the fire and much less by the ambient wind flow. However the model predicts a faster plume impingement on the upper levels of the measurement tower, whereas the arrival of fire at the position of the tower in the simulations is the same as in the experiment. We assumed that it was due to the model not being able to reproduce the actual wind profile at the tower location downwind a block of trees resulting in a 15% overestimation of wind speed at the upper level. The model also cannot incorporate the change in wind speed and direction that was observed during the initial development of the fire in the experiment and was likely to delay this impingement. The current technique used to set up the ambient wind field in the simulations does not allow to take into account such changes in ambient wind speeds that are likely not due to the surrounding vegetation, but to larger atmospheric structures. This is in fact a good illustration of the challenge that represents such model-experiment comparisons. The fact that the ambient wind during the fire was not known (not measured at a point not influenced by the fire) did not help with understanding the differences between predicted and measured horizontal wind speed during the fire passage. It is worth noting also that the model showed a clear effect of clearing the fuel at the tower base on temperature and velocity, which is important for design of future experiments. Finally, the drawbacks of the experimental measurements and the influence of ambient wind fluctuations that cannot all be captured by the model do not allow conclusive comparisons regarding turbulent statistics during the fire period.

These results encourage us to continue the assessment of the model using more recent experiments such as FireFlux II that benefit from progress in fire instrumentation and to simulate a diversity of situations that would help design future experiments by testing the sensitivity to environmental conditions and ignition scenario or the relevance of measurement devices.

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