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Statistics of highly concentrated VOC events released by turbulent mechanism over a flat forest

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ABSTRACT: During a forest fire, a possible scenario to explain sudden and dangerous eruptions is the ignition of volatile organic compounds (VOC) gas pockets. The latter could be created by the topography such as canyons or valleys but the wind-induced shear layer over a flat forest can also be responsible for concentrated gas pockets ejections. In the present work, the authors are investigating the statistics of highly concentrated COV releases over a flat forest through wind tunnel modeling. The number, the duration, the strength and the return period of gas pockets are studied.

1 INTRODUCTION

In forest fires, a possible scenario to explain sudden and dangerous fire eruptions (also called accelerated forest fire) during a forest fire is the ignition of volatile organic compounds (VOC) gas pockets (Viegas et al., 2011). This scenario is supported by the fact that the natural emission of VOC from the vegetation is highly increased under a thermal stress, Chetehouna et al. (2014) observed an emission rate multiplied by 8 between 50°C and 150°C. The literature also reports the behavior of firefighters who ran away because of a strong odor or when the vision became hazy (Viegas et al., 2011). These testimonies substantiate the role of highly concentrated gas pockets in sudden forest fire eruptions.

The accumulation of VOC can be due to the shape of the relief (a canyon or a valley) where the gas may be trapped. In the wind tunnel study by Coudour et al. (2014), time-averaged VOC accumulations were observed up to 4 times the averaged concentration inside a 100° angle V-shape valley covered with forest. However, extreme fire events were also reported in flat terrains (Viegas et al., 2011). In such configuration, the wind blowing over the forest induces a shear layer that increases the mixing between the forest and the free atmosphere. Observations by Conan et al. (2015) using wind tunnel experiments demonstrated the major contribution of coherent structures in the gas exchange between the forest area and the free atmosphere and shown that 70% of the highly concentrated gas pockets were linked to ejections. In this study, events of more than five times the mean concentration were observed above the forest. It is important to note that several variables such as the atmospheric stability and the leaf density are observed to drive the scalar transport within a vegetation canopy (Dupont et al. 2012).

In the present work, the authors propose to describe the statistics of the COV releases modeled in the wind tunnel. The mean concentration, number, duration and period of return

of highly concentrated gas pocket are presented and the probability of extreme events is evaluated by an EVA (Extreme Value Analysis) in order to estimate the period of return of extreme events. An attempt is performed to extrapolate wind-tunnel results to the field in order to evaluate the possibility for VOC to contribute to accelerated forest fire.

2 EXPERIMENT SET-UP

2.1 Wind tunnel and forest model

In this study, the atmospheric test section of the “Lucien Malavard” wind tunnel at the University of Orléans (France) was used. The test section is 3 m high, 3 m wide and 15 m long with a maximum speed of 15 m.s^{-1} at one meter height. Atmospheric boundary-layer conditions are developed along the length of the inlet fetch reproducing neutral wind conditions at a scale of 1/400. More information about the inlet flow conditions such as the turbulent profiles or the turbulent spectra are available in the study by Conan et al. (2015).

Similarly to the study of Aubrun et al. (2004), the forest is modeled on the wind-tunnel floor by a porous media constituted of metallic mesh cylinders in staggered arrangement (Fig. 1). The leaf area index is $\text{LAI} = 10.5$. An area of 3 m in the wind directions and 1 m in the crosswind direction is installed. The forest model is 0.05 m high representing an $h = 20 \text{ m}$ forest canopy.

The forest model is equipped with a gas injection device to mimic the VOC release within the forest. The flow-rate is adjustable with a precision of 0.5% and equally distributed in 400 tubes releasing gas inside the forest on a surface of 1 m^2 . In this study, aerodynamic mechanisms are investigated independently from buoyancy effects, therefore, ethane gas was chosen because its density is less than 5% higher than air and it is easily detectable by a flame ionization detector (FID).

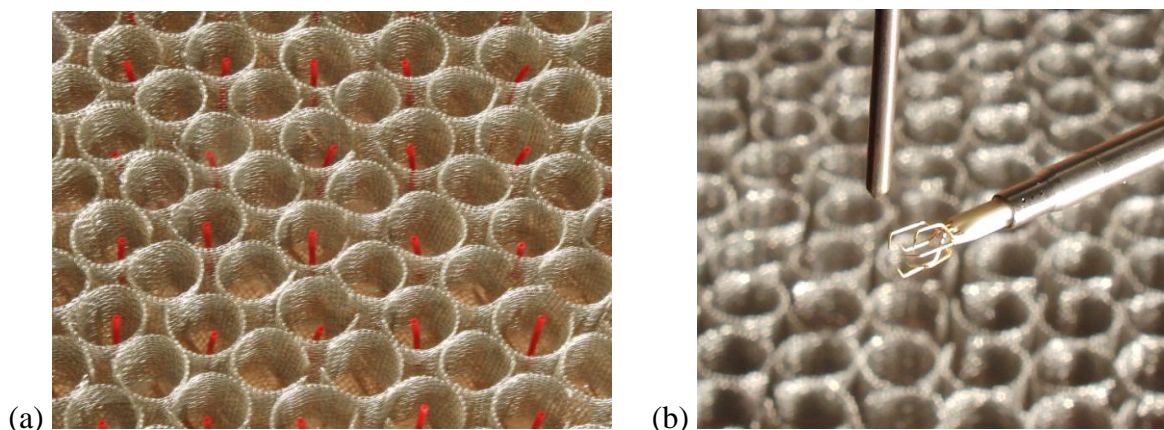


Figure 1: (a) Metallic rings arrangement equipped with tubes for the gas emission. (b) FID and triple hot wire set-up for the measurement of the concentration flux.

2.2 Measurement techniques

To characterize velocity and concentration fluctuations, a device combining a three components hot-wire anemometer (3CHW) and a fast FID was set-up to allow the simultaneous measurement of momentum and scalar fluxes. The 3CHW was calibrated for

velocity and direction using a Dantec Dynamics Hot-wire calibrator. The frequency response was set to 10 kHz and the bias error is estimated at 2.5 %. Measurements with and without gas emission did not present deviations above the measurement error.

The FID was calibrated using a certified calibration gas. A bias error of +/- 5 ppm (parts-per-million in molar fraction) was observed in the FID measurements. In the test conditions, the FID frequency response was 50 Hz. The FID signal has a time shift due to the travel time between the needle and the combustion chamber. This time delay was calculated using a software tool provided by the manufacturer and applied to the concentration time series in order to synchronize it with the velocity measurement from the hot-wire. The simultaneous acquisition of the concentration and velocity signals was performed at 300 Hz with an anti-aliasing filter at 100 Hz. Measurements were performed at $x = 20h$ from the forest leading edge.

The measured concentration was normalized by the flow-rate per unit area, Q_S ($m^3 \cdot s^{-1} \cdot m^{-2}$), and by the reference wind speed, U_{ref} , taken at $z = h$ such as $C^* = \frac{C \cdot U_{ref}}{Q_S}$. The

repeatability and the validity of the normalization were verified by repeating tests with varying U_{ref} and Q_S (see Fig. 2). The maximum difference found is 10%.

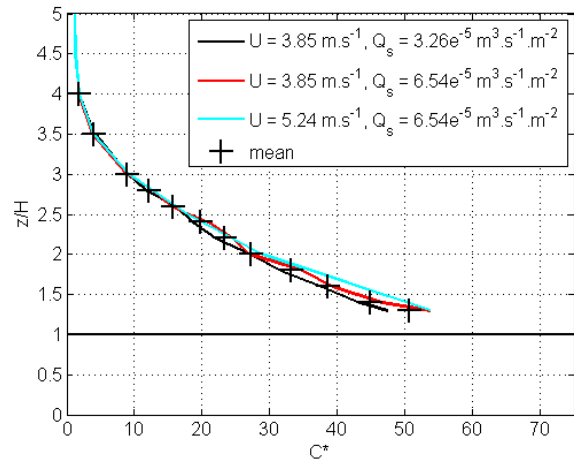


Figure 2: Normalization of the concentration measurements.

3 EXTREME VALUE ANALYSIS

An extreme-value analysis (EVA) is performed on the wind-tunnel measurements of concentration time-series using the peak over threshold method (POT). The method is well described in Coles et al. (2001) and Reiss et al. (1997). The principle is to select a threshold and to model exceedances with an asymptotic distribution: the global Pareto distribution (GPD). This technique allows for the description of extreme events and for the extrapolation to rare events not observed in the dataset. It is used by Palutikof et al. (1999) and Ceppi et al. (2008) on extreme wind speed observations and by Kuchenhoff et al. (1996) on pollution data.

3.1 The peak over threshold method

The procedure for concentration exceedances detection in the dataset follows several steps: data cleaning, peak detection, de-clustering, and, finally, GPD fitting.

In the first step, the dataset is cleaned by removing isolated aberrant values coming from sensor saturations. Those points, if present, are removed from the analysis. Then, POT are detected (black dots in Fig. 3) by taking the maximum

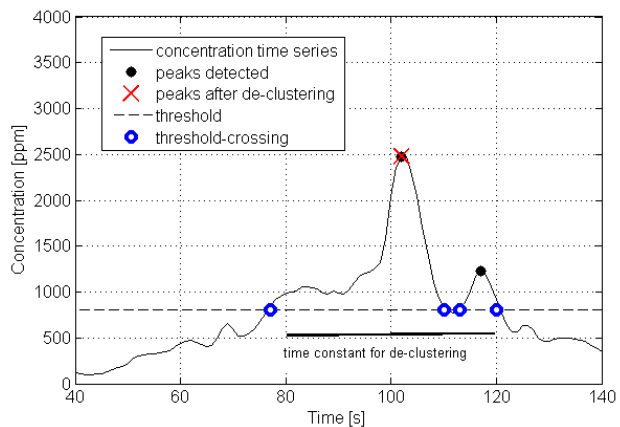


Figure 3: Example of application of the exceedances detection procedure. Two peaks are here detected (black dots) over the threshold (dashed line). After de-clustering, only the highest is kept because they belong to the same event (separation time is below 40s).

concentration value between two consecutive threshold-crossing points (blue circles in Fig. 3). The selection of the threshold τ is discussed in Sect. 3.2.

The POT method requires exceedances to be independent. In the present dataset, concentration extremes are closely linked to flow fluctuations (see Conan et al., 2015) so they may be associated to turbulent structures. Therefore, a minimum separation time is set based on the flow statistics. The integral time scale of the flow is measured to be 20 s (full scale) so to ensure independence, the minimum separation time is set to twice this value, 40 s. Extremes are then processed to keep only independent events (Fig. 3). Only the highest exceedance of several dependent peaks is kept. This procedure is called de-clustering.

Once detected, exceedances are fitted with a GPD assuming that the threshold is high enough so that the number of exceedances is low and Poisson distributed. The GPD gives the relation between the return level (RL) and the return period (RP) such as:

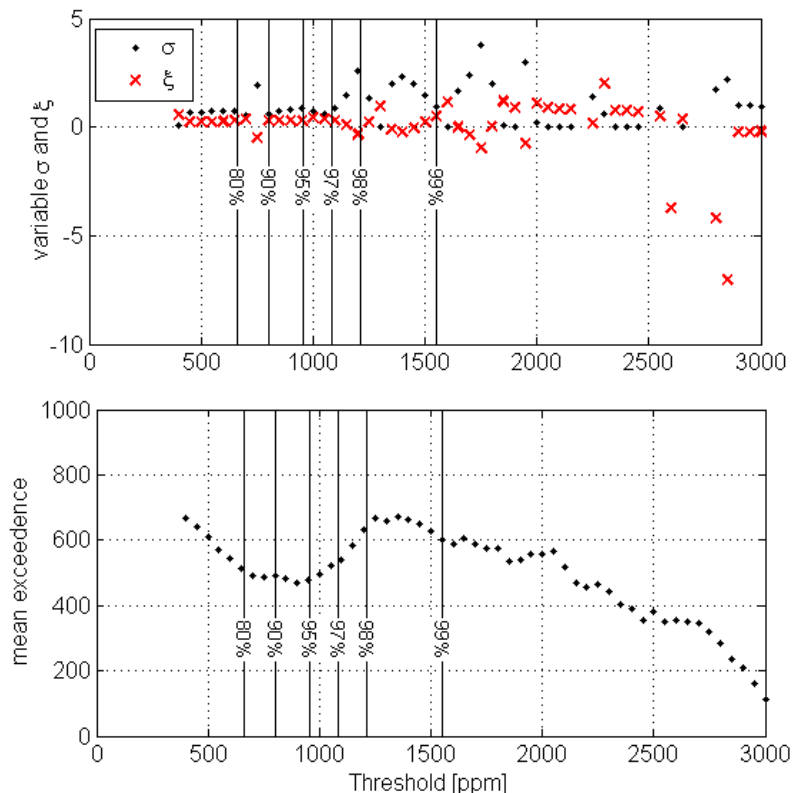
$$X_N = \tau + \frac{\sigma}{\xi} \left[(\lambda N)^\xi - 1 \right] \quad (1)$$

with X_N the RL of a period N (RP), (σ, λ, ξ) the parameters of the GPD, and τ the threshold. The RL is defined as the exceedance observed once in a RP.

3.2 Threshold selection

The selection of the threshold is an important issue for the analysis because it should be high enough to have only extreme events but low enough to have a sufficient number of samples to analyze. To help for the selection, the variables of Eq. 1 are plotted in function of the threshold value in Fig. 4 together with the mean exceedance. Following Coles et al (2001) ξ and σ need to be independent on the threshold value and the exceedance plot should have a linear slope. That leads to take the threshold between the 97th and the 98th quantile (see Fig. 4). However, between the two possibilities mentioned, the ξ parameter varies between positive and negative values changing in an important manner the interpolation (Eq. 1). Both thresholds are considered in Sect. 3.3.

Figure 4: Diagnostic plot for selecting the threshold. Parameters σ and ξ (top) and mean exceedance plot (bottom). Vertical lines represent the quantiles.



3.3 GPD

The relation between the RL and the RP is presented in Fig. 5 (left). The RL is given relative to the normalized concentration at the top of the forest canopy ($C^*/C^*_{h=1}$). The RP is given at full scale. Observations in the wind tunnel (dots and crosses in Fig. 5) report RL ~ 3 for RP = 1 hour and RL ~ 5 for RP = 3 hours.

The fitting to a GPD is presented for two thresholds (97% and 98% quantiles) in Fig. 5 (left). The two thresholds lead to a different extrapolation for long term RP but they give an idea of the probability of appearance of extreme events not recorded in the experiment. For a RP = 10, the RL is between 5.5 and 7. For a longer period of RP = 100 hours (~ 4 days), which is realistic giving that a forest fire can last several days, the different approaches give $7 < \text{RL} < 15$.

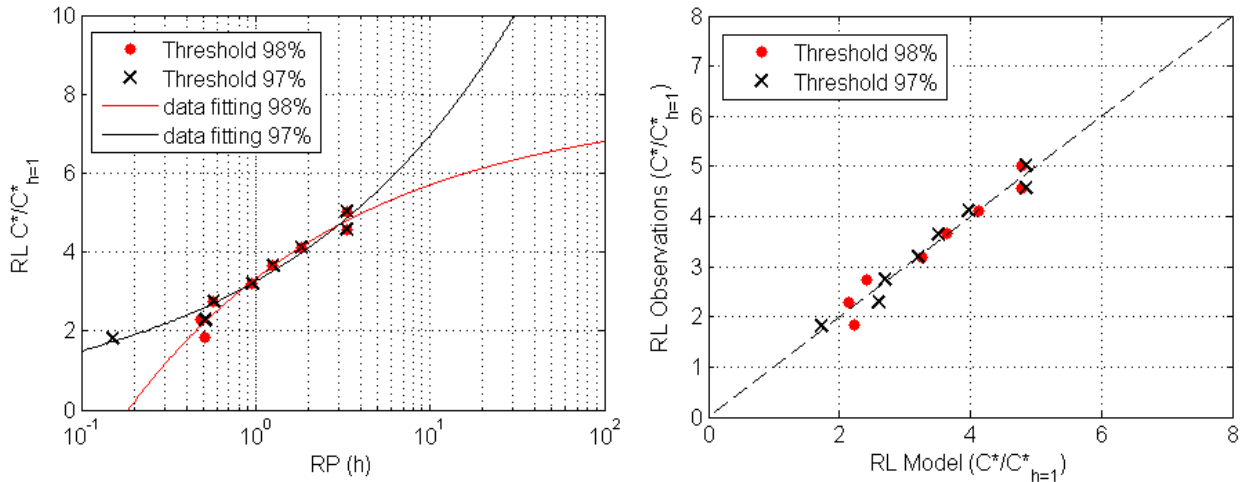


Figure 5: GPD fitting on wind-tunnel observations. $Z/h = 1.3$ (left) and Quantile–quantile plot for the two thresholds selected (right).

The scatter plot presented in Fig. 5 (right) enlighten the good agreement of the GPD fittings.

4 EXTRAPOLATION TO FIELD DATA

Assuming the similarity hypothesis to be applicable to the full scale, the dimensionless concentration C^* measured in the wind tunnel can be extrapolated to field observations. Measurements in the field from various authors give an order of magnitude of the VOC surface emission rate: Owen et al. (1996) and Owen et al. (2001) measured respectively $41 \text{ kg.km}^{-2}.\text{h}^{-1}$ and $50 \text{ kg.km}^{-2}.\text{h}^{-1}$. In the wind tunnel, $C^*=100$ at the top of the canopy. Assuming C^* is conserved, the equivalent concentration can be computed by $C = C^* Q_S / U$. With the velocity taken as $U=3 \text{ ms}^{-1}$, that gives $C \approx 5 \cdot 10^{-4} \text{ g.m}^{-3}$. According to Catoire (2005) the lower flammability limit (LFL) of VOC is approximately $\text{LFL} = 50 \text{ g.m}^{-3}$, the difference is roughly of 5 orders of magnitude.

In the work of Chetehouna et al. (2009), the emission can be multiplied by 8 if the vegetation is submitted to a temperature stress, this is the case in a forest fire. For a RP of a couple of days, the RL for extreme events is approximately 10 times the averaged value. Then, concentration peaks over the forest may be of the order of $5 \cdot 10^{-2} \text{ g.m}^{-3}$. This is still 3 orders of magnitude lower than the LFL.

For the conditions tested (passive scalar, neutral conditions, and no thermal effects), the extrapolation to field conditions never reaches the LFL. Consequently, the passive turbulent

transport of VOC above the forest canopy cannot be the only responsible for sudden fire eruptions.

Several aspects are likely to deviate the modeling from real conditions: VOC are not passive scalar but rather heavier-than-air gases that may lead to a higher gas concentration in the canopy compared to the level recorded in the wind-tunnel study, additionally thermal effects (not modeled) such as the atmospheric stability and the temperature in the presence of a fire may lead to different exchange mechanism through the forest canopy.

The extrapolation to field data is also subject to discussion. For instance, the increase of VOC emission due to temperature stress varies with the plant species considered, Barboni (2006) found a factor of 4000 between 80°C and 200°C in the case of the cistus. The factor of 8 considered here is then probably a minimum.

The study shown that the passive transport mechanism above a flat forest is able to release gas pockets with a concentration level more than 10 times the averaged concentration above the canopy. As such, it is a parameter to consider in the study of the scenario where VOC accumulation causes an accelerating forest fire.

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