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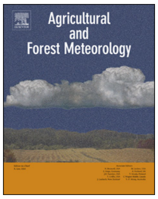

How stand tree motion impacts wind dynamics during windstorms

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ABSTRACT

Understanding how wind and trees interact during wind storms is crucial for better predicting forest wind damage. The complexity of this interaction is enhanced by the fragmented environment of forests. Here, we present an unprecedented field experiment (TWIST) where both the wind dynamics and the tree motion in the edge region of a maritime pine forest have been recorded simultaneously during four non-destructive wind storms. For three of them, the instrumented trees were under stand flow while for one of them they were under an edge flow. Our measurements demonstrate that the well-known characteristics of stand-flow dynamics remain valid under high wind conditions. Only the sub-canopy flow appeared more intermittent as canopy-top turbulent structures penetrate easier within the canopy due to the tree foliage reconfiguration. Under similar storm intensity, the tree motions were lower under edge flow than under stand flow due to the lower turbulence of the former flow while the mean wind speed was higher. This result demonstrates the importance of considering both the turbulence and the mean wind speed in wind risk models. No impact of tree motion other than tree reconfiguration were observed on the stand flow dynamics. On the other hand, for the edge flow, our measurements reveal a peak in frequency on the wind velocity fluctuations related to the fundamental tree vibration mode. This peak was especially visible at canopy top and in the upper trunk space under high wind conditions. Compared to the stand flow, we suspect that the velocity fluctuations induced by the tree motion emerge in the edge flow due to the lower background turbulence. Our edge storm was nonetheless not strong enough for tree motion to enhance flow turbulence and for trees to enter into resonance. These findings may suggest a higher susceptibility of near-edge trees to reach resonance than stand trees due to the motion of upwind trees in a lower background turbulence.

1. Introduction

Wind storms are responsible for significant damage in forests, affecting forest ecosystems (e.g., Mitchell, 2013) and leading to severe loss in their economic value (Schelhaas et al., 2003; Gardiner et al., 2012; Hanewinkel et al., 2013; Fischer et al., 2013). Understanding the occurrence of tree damage is complex as forests are often located in a heterogeneous-fragmented landscape with the presence of forest edges, modifying the wind dynamics loading trees. One key issue in better predicting the risk level of forests, lies on improving our understanding of the wind–tree interaction under high-wind conditions in such complex environment. In particular, it is still unclear how the main characteristics of the wind dynamics change with wind intensity as the tree motion increases.

The characteristics of the wind dynamics loading trees depend on the extent and morphology of the upstream forest. The wind dynamics over forest canopies is often differentiated between stand and edge flows. Stand flows or stand wind conditions are referred to as flows over a homogeneous canopy far from any edges, whose dynamics is in equilibrium with the canopy. Stand flows are homogeneous on both longitudinal and lateral averaging scales. Edge flows or edge wind conditions are referred to as flows over a canopy under the influence of an upwind edge separating a wild open space from the canopy. Unlike stand flows, edge flows are still adjusting to the canopy as they enter into the canopy. After a certain distance from the edge, the edge flow ends to a stand flow. This transition occurs when the mean vertical velocity at canopy top resulting from the deceleration of the flow within the canopy, has vanished. The distance for the flow to equilibrate with the canopy is usually about 8 to 10 canopy heights, with smaller values for denser canopies (Dupont and Brunet, 2008b). Belcher et al. (2008) proposed to quantify this distance as a number of canopy adjustment length scales L_c, where L_c depends only on bulk canopy properties (canopy drag coefficient and leaf area density). Dupont et al. (2011) showed latter that the length of the adjustment region depends also on the vertical distribution of foliage area. In presence of a deep and sparse trunk space, this distance can extend to more than 20 canopy heights.

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More information on the main characteristics of stand and edge flows can be find in Finnigan (2000) and Dupont et al. (2011), respectively.

Our current understanding on wind–tree interaction is mostly based on field measurements in stand wind conditions, and more importantly, it is based on measurements under moderate stand wind conditions (e.g., Sellier et al., 2008; Schindler, 2008). This is due to the difficulty of acquiring measurements during wind-storms. Flesch and Wilson (1999) investigated the interaction between wind and remnant trees along the heterogeneous environment of a sheltered cutblock, including upwind and downwind forests. However, their wind velocity measurements were limited to one level below tree height, and the tree motions were deduced from a simple mass-spring-damper displacement model. Hence, field measurements of wind dynamics and tree motion at both mid-stand and near-edge locations, and under wind-storm conditions, remain rare.

In stand wind conditions, trees sway in response to the passage of intermittent, energetic downward-moving gusts, known as large coherent eddy structures, evolving within unorganized random background turbulence (e.g., Gardiner, 1994). These coherent structures are mixing-layer type structures developing at the canopy top from the impingement of large-scale gusts coming from aloft (Raupach et al., 1996; Finnigan, 2000). Previous field studies identified these turbulent structures as the responsible for the largest tree displacements (e.g., Gardiner, 1994; Schindler, 2008). The energy absorbed by the tree from these structures is then dissipated by the natural vibration modes of the tree (Schindler et al., 2010), and by the crown collisions with adjacent trees in the case of a dense canopy (Rudnicki et al., 2008; Webb et al., 2013).

Under the action of wind load, branches and foliage reconfigure, reducing the tree frontal area and the pressure component of drag (e.g., Vollsinger et al., 2005; de Langre et al., 2012). This process of plant reconfiguration may enhance penetration of extreme gusts within canopies as observed by Pan et al. (2014) from a flume experiment and large-eddy simulations (LES). This streamlining of tree foliage has been described empirically by introducing a drag coefficient proportional to a power-law of the wind velocity whose negative exponent is known as the Vogel exponent (Vogel, 1989). Several studies based either on wind-tunnel experiments or linear stability analysis observed also a possible lock-in mechanism of the flow coherent structures onto the plant natural vibration frequency as the mean wind speed increases (Finnigan and Mulhearn, 1978a,b; Py et al., 2006; Gosselin and de Langre, 2009). This has, however, never been confirmed from field measurements, nor from the modeling of waving crops and forest motion using LES (Dupont et al., 2010, 2015). The discrepancy between linear stability analysis and LES was attributed to the presence of a nonlinear saturation mechanism in LES, independent on canopy motion, which was not considered in the linear stability analysis (Dupont et al., 2010).

In edge wind conditions, the flow is more dependent on the vertical structure of the forest and on its foliage density (Dupont and Brunet, 2008c; Dupont et al., 2011). Compared to the stand flow, the edge flow is usually characterized by a higher mean wind speed, with less turbulence (Irvine et al., 1997) as coherent structures developing at the canopy top are not yet fully developed (Dupont and Brunet, 2009). A substantial sub-canopy wind jet induced by the wind flow through the trunk space at the edge is often observed, causing the development of a positive momentum flux layer below the crown layer (Dupont et al., 2011; Dellwik et al., 2013). Less is known about tree motion under edge flow. It is often thought that the higher mean wind speed at the edge causes high wind load on trees, enhancing damage risk in strong wind conditions (Schindler et al., 2012), especially in edge regions adjacent to newly clear-cut areas, where trees have not acclimated to their new environment (e.g., Gardiner et al., 1997).

The goal of the present study is to investigate the sensitivity of the canopy wind dynamics to the wind intensity for stand and edge winds as tree motions increases. To that purpose, the wind dynamics and tree motion at the near-edge of a maritime pine forest was monitored during four successive non-destructive wind storms, three of them with stand wind directions (Kurt, Leiv and Marcel storms) and one with an edge wind direction (Egon storm). This experiment may represent the first documented wind–tree interaction dataset under both stand and edge wind-storm conditions.

2. The TWIST's field experiment

2.1. Site

The TWIST's field experiment took place from 1 to 14 February 2017 in a maritime pine forest (*Pinus pinaster* Ait.) at the Lagnereau site (44°43′ N, 0°46′ W) located at 1 km west from the Salles Integrated Carbon Observation Station (ICOS), in Les Landes region in south-western France.

The stand was about 200 × 200 m^2, with a mean tree height h of approximately 15.2 m and a mean stem diameter at breast height *dbh* of about 0.27 m. The forest plot was planted in 1996 in a regular array with 4.0 m spacing between adjacent rows and on average 3.8 m spacing between trees along each row. The stand density was about 660 trees ha^{-1}, with a leaf area index (LAI) of about 3.2. This last parameter was estimated following the allometric equations of Porté et al. (2000) established on maritime pine trees. The forest was characterized by a dense crown layer located between 7.5 m and 15.2 m, and a sparse and open trunk space below 7.5 m. The soil was covered with sparse bushes approximately 2 m high with a LAI of about 1.5. The ground surface was flat in all directions.

The forest plot was surrounded by similar stands in the North and South, by a sparser plot with higher trees in the West, by a lower plot in the North-West, and by open areas on the East (Fig. 1a). This configuration allowed us to study stand and edge conditions from this single site, by splitting the data into two wind sectors, western and eastern winds.

2.2. Measurements

A 20 m high pneumatic mast was erected at 1.2h from the eastern side of the forest plot, in a small canopy gap (Fig. 1a,c,d). Special care was taken to avoid trees hitting the mast and its shrouds under high wind conditions. On this mast, turbulent velocity components and sound virtual air temperature were measured simultaneously at 7.8, 12.1, 15.6, and 19.8 m (0.5h, 0.8h, 1.0h, 1.3h) above the surface using four ultra sonic anemometers sampling at 20 Hz (Fig. 1c). The first two anemometers (Gill WindMaster) were located within the canopy, in the upper trunk space layer and within the tree crown layer, respectively, and the last two (Campbell Scientific CSAT3-3B) at canopy top and above the canopy. All sonic anemometers were oriented toward the West.

The wind velocity measured at the ICOS site is used as a reference storm velocity u_{ref}. The ICOS site corresponds to a 13-year-old maritime pine forest where the wind velocity was measured continuously at 2h_{icos}, where the mean tree height was h_{icos} = 8.4 m. This site was wide enough to have negligible fetch effect in all wind directions, which makes this site ideal for a reference wind-storm speed for our experiment.

Among the instrumentation installed on the site, wind-induced tree motion was measured on three trees surrounding the mast (Fig. 1d) from three biaxial inclinometers (Gemac, IS2BP090-O-CL). Tree 1 was 15.7 m high and located at 8.0 m south of the mast, Tree 2 was 15.5 m high at 11.0 m west of the mast, and Tree 3 was 15.2 m high at 4.0 m north of the mast. The inclinometers were mounted at 0.01h, 0.20h and 0.40h on each tree in order to measure the rotation of the soil-root system and the deflection of the stem. They were integrated in waterproof housings and fixed horizontally on the stem by using a spirit level and by activating the inclinometer automatic zero correction. Before installation, the inclinometers were calibrated in both x and y-