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INTERACTION OF TREES WITH BOUNDARY LAYER FLOW

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Abstract

In the context of air pollution control the flow conditions inside a roadside tree and an immission control planting were examined. While in undisturbed laminar flow the results clearly show a flow through the vegetation stand, the results of measurements taken in less ideal conditions are not so easily interpreted. While it is obvious that a large shrub or tree does not induce a deflection of incoming air flow, the results are ambiguous as to how the flow through the plant can be described.

Introduction

Our research group at the University of Karlsruhe is concerned with the potential of urban vegetation for particle filtering. Urban aerosols, especially respirable dust are gaining in importance in the debate on air pollution. The EU-directive 1999/30/EG on SO_2, NO_2, nitrous oxides, particles and Pb in the air sets threshold values of 40 µg/m³ for particle load in the air from the year 2005 on (to be reduced to 20 µg/m³ in 2010) that will most likely be exceeded in urban areas if no reduction strategies are employed see LfU/UMEG 1999. As the better part of suspended particulates is produced by street traffic and therefore by multiple point sources, a reduction of particulates at their source is difficult. Roadside vegetation has been employed to reduce traffic-induced pollution for quite some time but it is difficult to put numbers on its filtering effect on particulates.
An important factor in the understanding of particle deposition on leaf surfaces are the meteorological boundary conditions, especially the behaviour of the air flow in the tree crown and its exterior shell, where the leaf density is highest. This can be said not only for trees but for shrubby plantings as well. Those are often employed in urban areas in order to reduce transmission of air pollution and noise. By officially calling these plantings 'immission control plantings' they are given a significant place in pollution control.
In this research project, systematic flow analyses have been conducted in a immission control planting in Tübingen and a deciduous urban tree in Karlsruhe.

Methods and instrumentation

Traditional measuring techniques like cup anemometer and wind vane are not appropriate for this problem as they are not accurate enough concerning the spatial resolution, react with too much delay and have too high a starting speed with lower wind speeds not being registered at all. Ultrasonic anemometers that work on the basis of differences in the travelling time of ultrasonic impulses, are best suited for measurements at low wind speeds. The drawback here is the minimum measuring distances which result in rather large proportions of the device and therefore in spatial limitations. Thermal anemometers allow the measure-

ment of wind speed at a high spatial accuracy. They measure wind speed by sensing changes in heat transfer from the measuring device to the surrounding air with an integrated correction including the ambient air temperature.
We used spherical thermal anemometers as well a miniaturised hot-wire thermal anemometers. The hot-wire anemometers have a volume of ca. 1/100 mm³ which allows an exact positioning down to the scale of millimetres. However, its small mass and free exposure of the device make it very susceptible to contact of any kind. Therefore, protective measures have to be taken that again result in methodical problems which will be discussed later.
Methodically, two different approaches were taken. First, continuous measurements were made during the whole campaign (several years), second, temporary field experiments were made at specific weather conditions with different instruments positioned in the vicinity of the studied object. This makes the measured wind speeds directly comparable. The measurements with the hot-wire thermal anemometers were taken in temporal sequences. They not only represent a sample of the spatial distribution but of the temporal variation as well. In the case of a convective boundary layer this poses a problem due to the strong temporal fluctuation of the wind speed over short periods of time. Thus, we use the continuous measurements – in particular the ultrasonic anemometers - as a reference by determining and interpreting the differences to those values.

Results

Measurements in an immission control planting in a stably stratified atmosphere

The experiments in an immission control planting were made during periods of a stably stratified boundary layer. The vertical component of the flux is considerably reduced and the horizontal, thermally induced flux dominates. During night-time, the driving forces are very often cold air masses near the ground that move downhill. These air movements are of a great significance for air pollution as they dominate the exchange of air and input of fresh air in urban areas in valley situations during periods when other mechanisms driven by large-scale pressure differences do not occur. The aim is to leave the open spaces relevant for these flows free from buildings or plantings. The question often occurs if plantings that are desirable in other aspects negatively influence the flow field in these situations.
In Agricultural climatology as well cold air flows are of high significance as they can cause unwanted frost damage to the crops. Frost protection plantings are planted and their effectiveness is justified by the fact that the air temperature in their lee is higher than windwards. Thus, a 'deflection' of the cold air is argued as their effect. In reality, the processes that occur inside the vegetation stands are largely unknown and further investigation on the matter seemed necessary.
A typical example of the variations of wind speed in such a stably stratified boundary layer is shown in figure 1. It is characterised by a regular pulsation and little noise. Thermally or dynamically induced turbulence is non-existent in the scale of the represented wind speeds. By determining trajectories one can prove that a deflection of the flow takes place only to a lesser degree. The bigger part of the incoming cold air flows through the grove. Wind spee measurement in the interior of the grove show a decrease in wind speed but an increase in its variation which can be interpreted as a measure of dynamic turbulence (Fig. 2). The turbulence again decreases in the lee as well as the wind speed. The turbulence- inducing effect of the grove extends into its lee. In a stable stratification turbulence results in an increase of vertical mass fluxes and thus in an entrainment of warmer air from above into the cold air mass near the ground. This results in an increase in temperature. Therefore, it would be wrong to interpret the leeward increase in air temperature as a deflection of the cold air.

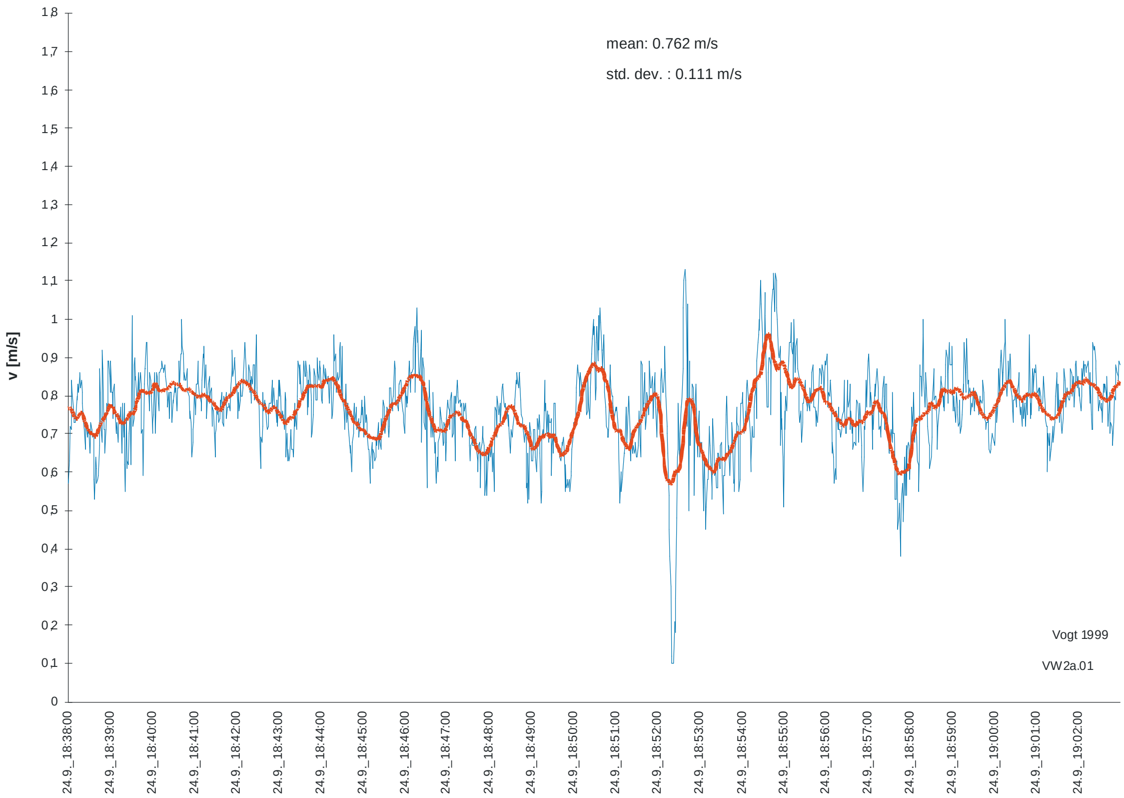

Figure 1: A typical flow in a stably stratified boundary layer at the site in Tübingen. Shown are the momentary wind speed and its moving average

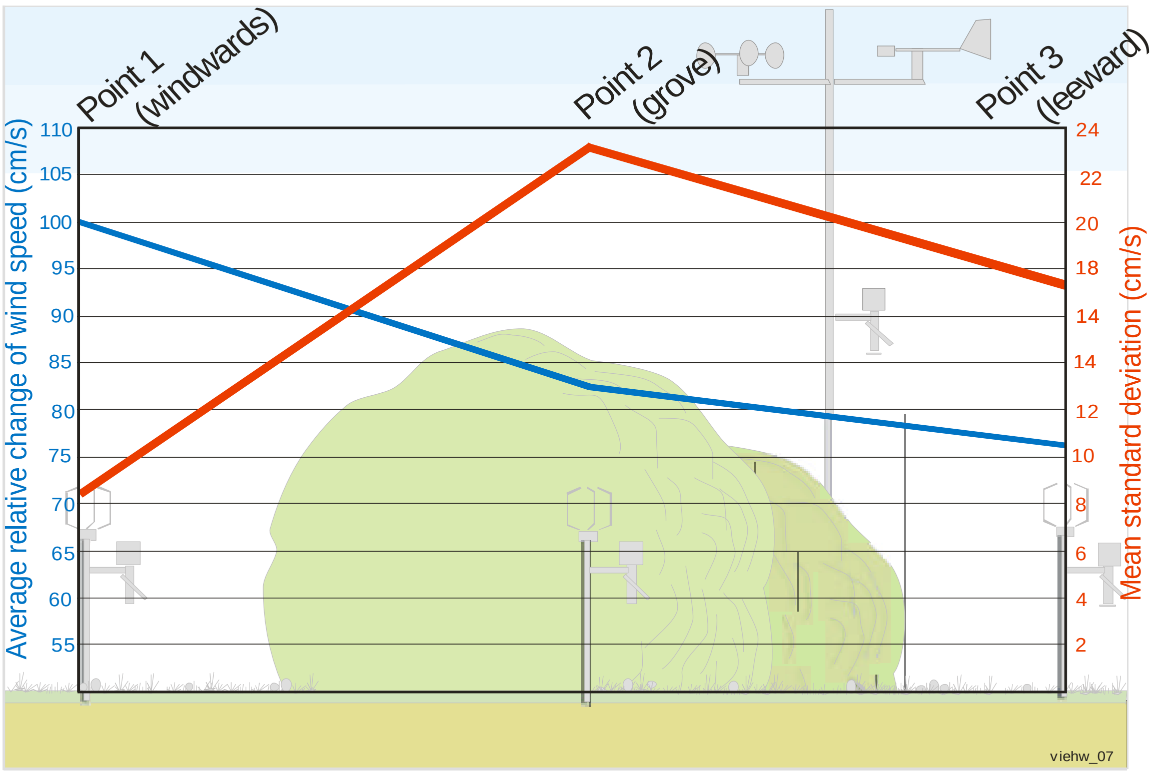

Figure 2: Normalised wind speed (decreasing) and its standard deviation (increasing) from the windward side of a large shrub to its lee.

Nevertheless, the induced turbulence decreases the existing horizontal gradient of temperature that is driving the air flow so that the flow slows down and finally dies.

Measurements in a roadside tree

In order to investigate the conditions of particle deposition on the surface of leaves, a larger scale is necessary. The measurements were taken in a roadside tree of the species *Acer platanoides* which stands in a row of similar trees near an arterial road in the city of Karlsruhe, Germany.
On this site, cold air flow is absent as well as periods free of turbulence – due to the high traffic volume. Under these condition which are typical for urban roadside trees different series of measurements were taken.
First, at a height of app. 4.6 m above ground hot-wire anemometers were used to examine the flow in the region of the leaves in the middle height of the crown. In the species *Acer platanoides*, the leaves are primarily situated in the outer shell of the crown with almost no leaves in its centre. This 'leaf mantle' of the crown shows a very regular alignment of the leaves if you look at it in more detail. Thus the tree achieves a very efficient light harvesting. Inclination and exposition of the leaves as well as the mean distance between the leaves vary only in a relatively narrow range.
In a typical sector of the crown between two leaves that are 104 mm apart, measurements at a high spatial resolution were taken (Fig. 3). In was inevitable to fixate the lower leaf where the measuring sensor was approached down to a distance of 1 mm. Figure 3 indicates the fixation of leaf and petiole.
The measurements were taken at an one-sec.-interval. Later they were averaged over 20 to 30 minutes and revised with respect to the errors that are part of all field data. After that, the difference to the time-parallel values of the reference station (ultrasonic anemometer at 5.5 m above ground outside the tree canopy) was calculated. This reference was necessary as the measurements could not be taken simultaneously. The main reason for that is the disturbance of the flow field by sensor that are positioned in close proximity to each other. Thus figure 3 shows positive values if the measured wind speed was higher than that at the reference point and negative values if it was lower. The ambient flow conditions can be described as a convective boundary layer with strong thermals combined with and intensified by traffic-induced turbulence.
As assumed the highest wind speeds occur in the middle between the two leaves. It is surprising, however, that there is an increase in wind speed at this level compared to the space outside the crown (positive wind speeds). In direction of the interior of the crown the wind speed decreases relative to the reference speed. There is only a slight decrease of wind speed when approaching the fixed leaf's surface. Even in 10 mm distance a positive value (+0.367 m/s) is recorded. Still, the wind speed is greater than outside of the crown. Only at 2 mm above the surface, the wind speed drops under the reference value (-0.077 m/s). A significant drop in wind speed can only be observed at 1 mm above the fixed leaf (-0.307 m/s). Trying to appraise the volume flux through the crown based on these conditions, the flow moves completely through the crown, not around it. The volume flux density forces the flow to go around leaves and branches only but not around the crown as a whole. This is of great significance in the question of particle deposition as the relatively high wind speeds near the surfaces allow for an effective inertia-driven deposition of particles bigger than 1 µm. In other words: The tree can fulfil its properties as a particle sink due to the specific flow conditions.

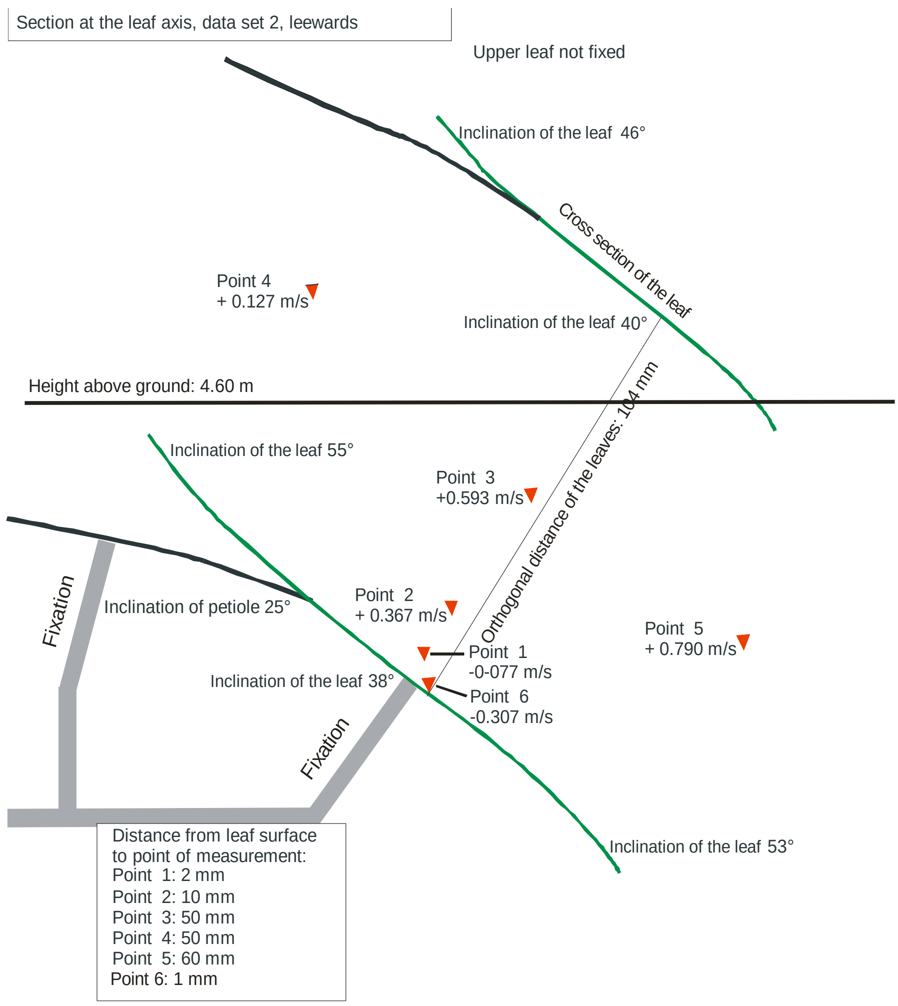

Figure 3: Measurement set-up for hot-wire anemometer measurements

Horizontal profile through the crown of the tree

To determine the variation of the flow dependent on the direction of the incoming flow, five thermal anemometers were placed at the same height in different places in the crown. An additional anemometer was placed directly under the crown near the trunk. The alignment mainly followed the direction of the street which is slightly turned compared to geographic north. The positions of the first five anemometers are shown in figure 4. For easier reading, they will be referred to a north, east, south, west and middle. As reference data, the readings of a cup anemometer and wind vane in 13 m above ground were used as well as the data gathered by a three-dimensional ultrasonic anemometer north of the tree near its surface. The five thermal anemometers and the ultrasonic one were placed at a height of 5.5 m where the crown has its maximum girth, the thermal anemometers being placed just inside the area where most of the leaves are situated (‘leaf mantle’).

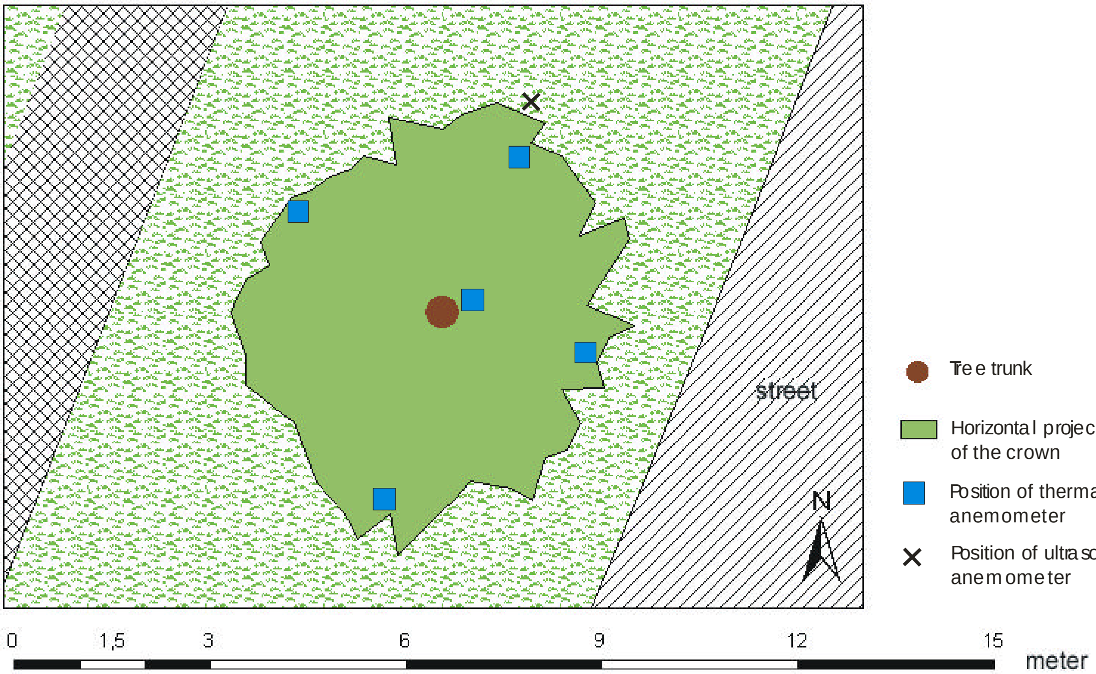

Figure 4: Measuring set-up the height above ground is 5.5 m, the sensor below the crown and the cup anemometer are not shown in this picture.

Measurements were taken over a time period of three days in June 2002 with a rather similar surrounding flow. The data presented here is from one period during daytime and two during night-time. In all three periods, the wind speed recorded was quite low, the traffic-induced turbulence is more significant during daytime but cannot be assumed zero at night as there is still some traffic there. The direction of the incoming flow is N respectively NNE at all times which is parallel to the street and the row of trees in the middle of which the object of our studies is situated. The measurements were taken at a period of 10 seconds and later integrated over a period of 1-2 hours. The wind vane and cup anemometer recorded 10-min means but were integrated over the same time period as the other sensor's data.
The results (table 1) show an interesting pattern: While the wind speeds in the north and east are predictably relatively high and those below the crown even higher than that due to the lack of obstacles there, a considerable increase of wind speed in the leafless inner crown takes place. The leeward sensors recorded only slightly lower values than the windward ones, but in one case (period 2, W) even higher than those in the north.

	N	E	S	W	Middle	Trunk	USA	13 m	Mean wind direc.
Period 1 (night)	0,25	0,27	0,21	0,20	0,35	0,49	0,28	0,61	NNE
Period 2 (night)	0,15	0,17	0,13	0,19	0,22	0,28	0,19	0,58	N
Period 3 (day)	0,54	0,49	0,42	0,35	0,66	0,96	0,44	1,53	NNE

Table 1: Mean wind speeds at 5.5 m above ground. Numbers shown are absolute wind speed in m/s

We suppose the increase in the crown's interior is due to a certain canalisation effect of the crown structure. This leads to an increase of the flow after it passes through the obstacles (leaves). In the lee of the crown usually a decrease in wind speed can be observed. The relatively high wind speed below the crown near the trunk may be due to a partial deflection of the flow of traffic- induced turbulence.

Summary and perspectives

The presented results give an idea of the problems specific to spatial high-resolution flow measurements in vegetation canopies. Many problems are not solved yet and our research group will pursue them further. A particular problem is the indispensable fixation of the leaf. We do not know any technique that allows exact positioning of the measurements above a leaf freely moved by the wind.

The present results, some of which are presented here, are not yet consistent. Their dependence on the meteorological conditions, especially on the stratification and the degree of turbulence must be examined further.

Last but not least, the influence of the leaves' morphology has to be taken into account. The smooth surfaces of *Acer platanoides* surely show another behaviour in the flow as the hairy one of *Tilia platyphyllos* which is another popular roadside tree. In the future course of the research programme, we therefore included an intensification of the measurements to affirm these results as well as an expansion to other tree species. Furthermore, the effects of vegetation on the flow field in urban green spaces has to be estimated. This is the link to urban meteorology where these results should be part of a line of argument with the aim of protecting urban vegetation against the pull of other land uses.

Acknowledgements

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