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The use of the gradient method to monitor trace gas fluxes over forest: Flux-profile functions for ozone and heat.

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Abstract

This study aims to assess the relation between fluxes and profiles above forest for trace gases. To this purpose the flux of ozone to a Douglas fir forest was measured continuously by eddy correlation for seven months in 1993. During the same period vertical profiles of air temperature and ozone concentration were determined over the forest. In addition several turbulent parameters were recorded.

From the observed temperature profiles and sensible heatfluxes flux-profile functions could be derived. Due to the scatter in the vertical profiles, flux-profile functions for ozone could not be derived with the same confidence. However, a significant difference with the observed flux-profile functions for heat could not be detected. Fluxes of ozone calculated according to the gradient method using the derived functions for heat showed very good agreement with the fluxes observed by the eddy correlation method. This result shows that the gradient method can be used with good results over forest when local flux-profile functions are used.

1. INTRODUCTION

To asses the achievement of environmental policy goals regarding the input of acidifying species by atmospheric deposition a monitoring system needs to be available. Such a monitoring system is now being developed for sulphur dioxide and ammonia in the Speulderbos, a Douglas fir stand in the centre of the Netherlands [1]. The deposition will be monitored by the micro-meteorological gradient method. This indirect method is used because monitors fast enough to be used in the eddy correlation method are not available. The deposition flux is determined from measurements of the concentration of gases at several heights above the forest and a turbulent diffusion coefficient k_z. Over low vegetation this diffusion coefficient can be determined from empirical flux-profile functions given in the literature. Because of the large roughness and the use of towers barely extending above the canopy the situation is more complex over forest. Measurements may take place in the so-called roughness layer where large deviations from classical flux-profile functions may be expected. To support calculations of the flux from the concentration gradient observed in the Speulderbos, local flux-profile functions are required.

To determine the flux-profile functions over Speulderbos an automatic system capable of measuring the flux and the concentration gradient of ozone was operated continuously in a 36 m tower for nearly eight months in 1993. From these measurements flux-profile functions for heat and ozone were derived. In this paper the experimental set up is described and the results of the measurements are reported.

2. THEORY

The eddy correlation method is considered a reference method to measure the fluxes of trace gases to the surface. The average flux is equal to the covariance of the vertical component of the wind velocity (w) and the air concentration (c):

$$F = \overline{w \cdot c} \tag{1}$$

In order to measure the contribution of all eddies to the flux, fast response sensors are required. These are often not available for important trace gases such as sulphur dioxide and ammonia. Therefore gradient methods are often applied. Principle to the gradient method is the flux-gradient assumption. Similar to Ficks law the flux F_i of a component i is calculated from:

$$F_i = -k_z \frac{\partial c_i}{\partial z} = -\frac{k u_* z}{\Phi_c\left(\frac{z}{L}\right)} \cdot \frac{\partial c_i}{\partial z} \tag{2}$$

The deposition velocity v_d is equal to: $-F_i/c_i$. c_i is the concentration at a reference height $z=h-d$. Where h is the height above ground and d is the so-called zero displacement height.

k is von Karman's constant (taken equal to 0.4), u_* the so called friction velocity and $\Phi_c(z/L)$ is the dimensionless flux-profile relation. L is the Monin Obukhov length scale defined in [2]

When gas fluxes are measured the flux-profile functions are often taken equal to the flux-profile function for heat Φ_h. Empirical values for Φ_h are given in the literature [2]. In principle the functions for trace gases could be different to those of heat although field experiments over grassland [3] showed reasonable agreement between turbulent exchange coefficients for heat and ozone. Over forest such measurements have not been reported. Especially the displacement height for gas could be different from the one for heat. Therefore the objective of this study was to determine Φ functions for a trace gas in Speulderbos.

In an earlier study carried out in 1988 and 1989 in the framework of the acidification programme local flux-profile functions (Φ_h) were used together with a displacement height of 11.5 m. These functions were derived from measurements carried out at the site [4]. A height dependent correction factor α was used to correct the flux-profile functions Φ for heat given by Dyer and Hicks [5]:

$$L<0 \quad \Phi_c = \alpha\Phi_{(Dyer,\ Hicks)} \quad with\ \Phi_{(Dyer,\ Hicks)} = \left(1-16\frac{z}{L}\right)^{-\frac{1}{2}} \tag{3}$$

$$L>0 \quad \Phi_c = \Phi_{(Dyer,\ Hicks)} - (1-\alpha) \quad with\ \Phi_{(Dyer,\ Hicks)} = 1+\beta\frac{z}{L}\ with\ \beta = 5.2 \tag{4}$$

Since then the forest has grown by a few metres. As a consequence the values for α and the zero plane displacement height d will have changed.

3. METHODS

3.1. Description of the site

The measurements were carried out in a roughly 30 year old Douglas fir stand [2]. The stand is homogeneous of an area of 2.5 ha. It is surrounded by oak and larch. The stem density is nearly 800 stems per hectare. The height of the trees was about 18 to 20 metre. The one-sided leaf area index varies over the years between 10 and 17 [6]. A diagram of the site is given in [2].

3.2. Instruments

The experimental set up is schematically presented in Figure 1. Central to the instrumentation is a sonic anemometer, a Kayo Denki DAT 310 with TR61 probe mounted at the 30 metre level on a boom extending some 3 metre from the tower on the South-West side. The fast response ozone monitor (7) is mounted on a smaller boom in a way that the air inlet was located 25 cm from the sonic centre. At 24, 26.5, 30 and 35 metre above the ground high accuracy temperature sensors (8) are mounted on smaller booms. Relative humidity of air is obtained from a Vaisala instrument with a capacitive sensor. Radiation instruments for net radiation (Schenk 8110), Global radiation (Li-Cor) and Skye SKP 215 sensor for Photosynthetically Active Radiation (PAR) are mounted on the 30 metre level.

Air is drawn from the inlets at the same heights as the temperature sensors to a central manifold located near the instruments at the 28 m level. Using a computer controlled valve system the height from which air is drawn through the manifold can be selected. The ozone concentration is determined using a Bendix 8002 with ozone detection based upon the chemiluminescent reaction of ozone with ethylene.

Using this set up the air concentration can be determined four times at each height within each cycle of 20 minutes. In [9] and [10] several tests with the set-up are described. An experiment with all tubes sampling from the same height showed that systematic differences in the concentration observed with the different tubes were not detectable and less than 0.2%. Typically this leads to maximum errors in the deposition velocity of 0.35 mm/s. Random fluctuations in v_d however can be as high as a few mm/s.

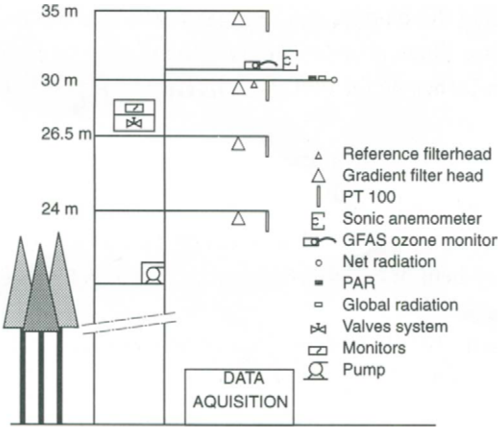

Figure 1. Instrument set up in the meteorological tower at Speulderbos.

3.3. Calculations of the flux-profile functions from data

For every 20 minute interval the flux-profile functions Φ for heights 1 and 2 were calculated from the eddy correlation fluxes and gradients.

$$\Phi_H = -\frac{\kappa u_* z}{\overline{w\Theta}} \frac{(\Theta_2 - \Theta 1)}{(z_2 - z_1)} \tag{5}$$

$$\Phi_C = \frac{-\kappa u_* z}{\overline{wc}} \frac{(c_2 - c_1)}{(z_2 - z_1)} \tag{6}$$

with Θ_z the potential temperature calculated from the observed air temperature T as $\Theta_z = T + \gamma$ with γ the dry adiabatic lapse rate.

In order to use only good quality data measurements in the wind sector 315° to 45° were excluded because the measured turbulent parametres may be affected by the tower. Measurements during sunrise and sundown were also excluded. Only cases with a monotonously increasing or decreasing temperature gradient and with the absolute value of the heatflux larger 18 W/m^2 were considered.

The ozone flux observed using the eddy correlation method was corrected for spectral response according to [11]. Using an experimentally determined response time for the ozone monitor of 0.1 sec the average correction was only 4% with maxima up to 8%. The flux-profile function for ozone was only calculated when the following criteria were met:

- the flux of O_3 was larger than 0.1 ppb.m.s^{-1}.
- the standard deviation in the O_3 concentration measured at one height was smaller than 5%.
- the concentration of O_3 is larger than 15 ppb.
- the error in v_d due to instationarity in the O_3 concentration is smaller than 5 mm/s [see 12].

The purpose of applying these additional criteria is to reduce the noise level in the calculated flux-profile functions. There is no indication in the results suggesting that the above criteria have a systematic influence on the results.

4. RESULTS AND DISCUSSION

All instruments were operated from December 1992 to September 1993. For several different reasons a large fraction of the data obtained in the wintertime appeared to be unreliable. For the analysis presented here only the data from the period April 1993 to September 1993 were used.

Roughly 2500 successful twenty minute measurements of the eddy correlation flux were available. The gradient measurements yielded nearly 3500 successful runs.

4.1. General

Figure 2 shows a typical result of the eddy correlation measurements on July 9 and 10, 1993. A diurnal cycle of the canopy resistance R_c, calculated as in [4], is clearly detectable with values going down to around 70 s/m during the day and values of 500 s/m at night. The actual results are plotted without any smoothing in order to give an impression of the good quality of the data. This diurnal cycle is probably linked with uptake of O_3 by stomata.

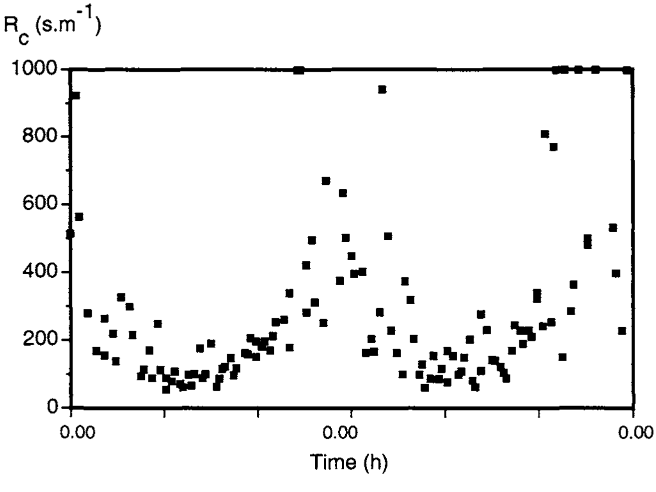

Figure 2. The canopy resistance to uptake of O_3 calculated from eddy correlation measurements at Speulderbos (July 9 and 10, 1993).

The dependency of the canopy resistance on PAR is illustrated in Figure 3a. Figure 3b shows the dependency of the canopy resistance of the vapour pressure deficit. Especially the dependency of the vapour pressure deficit is quite strong, although it is important to realize that several cross-correlations between the air temperature, PAR and vapour pressure deficit exist. Therefore, a more detailed interpretation is required. In an earlier study carried out in Speulderbos the effect of several parameters on the stomatal resistance to water vapour, calculated from eddy correlation measurements, was investigated. A strong influence of vapour pressure deficit and radiation and hardly an effect of canopy temperature was also observed [19].

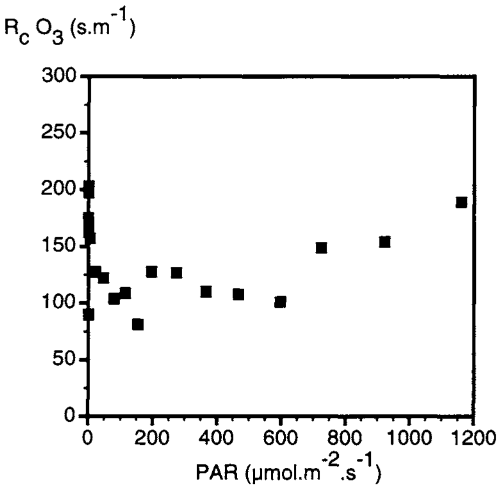

Figure 3a. The median canopy resistance of O_3 calculated from eddy correlation measurements above Speulderbos as a function of Photosynthetic Active Radiation.

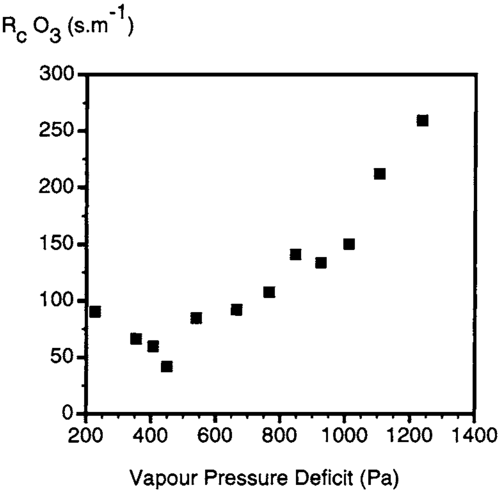

Figure 3b. As 3a for vapour pressure deficit (only daytime results)

The average ozone flux was around 0.15 ppb m/s with a standard deviation of 0.12 ppb m/s. The average O_3 concentration was equal to 35 ppb. The average deposition velocity was 7 mm/s. The median canopy resistance calculated from the measurements was 150 s/m. A more detailed statistical treatment of the date is given in [10].

These results fit quite well with literature data. Greenhut [13] reports aircraft measurements over coniferous forest in southern New Jersey with an average canopy resistance of 50 to 400 s/m. Lenshow [14] reports a canopy resistance of 50 s/m. Using the eddy correlation method Wesely [15] found values varying between 150 and 400 s/m with values up to 1500 s/m at night.

4.2. Flux-profile functions

A specific averaging procedure was used to calculate flux-profile functions. After all selection procedures around 500 twenty minute cases were left. The arithmetic average of these Φ functions for ozone in a certain stability interval z/L shows too much scatter. The large scatter is caused by the magnitude of the concentration gradient as well as the magnitude of the fluxes. Especially at (near) neutral conditions (windy, overcast) when the ozone concentration is low the deposition flux becomes very small. Only between 24 and 35 metre the difference can be observed well above the detection limit.

In order to reduce the large effect of outliers a robust statistical treatment is required. Therefore several averaging procedures were compared [10]. The larger temperature data set showed less scatter and was used as a database to test these procedures. Best results were obtained using a robust statistical method proposed by the Analytical Methods Committee [17]. With this method the average is calculated on the basis of the 50 and 75 percentile values thereby minimising the influence of outliers. For heat the difference in the results obtained using the various procedures appears to be small. For O_3 only the robust methods gave useful results. Based on the similarity in transport mechanisms it was assumed that the procedures used for heat could be applied for O_3 with confidence as well.

Figure 4 shows the flux-profile functions calculated for heat for the heights 30 to 35 m. A displacement height of 15 m was assumed as 75% of the height of the trees [16]. It is important to realise that the zero displacement height was now chosen to be 15 metre rather than the 11.5 metre chosen earlier. This difference is related to the growth of the forest over this period the forest which was between 0.6 to 0.9 m per year and therefore some 3 m over these years [6]. It appears that the functions can be described quite well with small corrections to the existing flux-profile functions. The values of the Φ_h function calculated using classical equations (3) and (4) with α equal to 0.9 are also plotted. It was noted that a slightly better comparison between the observations and the functions could be obtained when the coefficient β in the flux-profile functions was taken to be 7 rather than 5. Similar results are also reported by Bush [2].

Table 1 shows the data for the other height intervals as well. The correction factors compare quite well with the results found in the earlier study [4] . As was observed earlier the deviation from the original functions increases when the canopy is approached.

Table 1
Values of α to correct flux-profile functions as in equations (3) and (4) for heat for different height intervals h_1 and h_2. Assuming a displacement height of 15 m the effective height z_{eff} for which the Φ is valid is calculated from: $z_{eff} = \sqrt{z_1 \cdot z_2}$

Interval h_2-h_1	z_{eff}	α
24 - 26.5	10.2	0.75
26.5 - 30	13.1	0.8
30 - 35	17.3	0.9
24 - 35	13.4	0.75

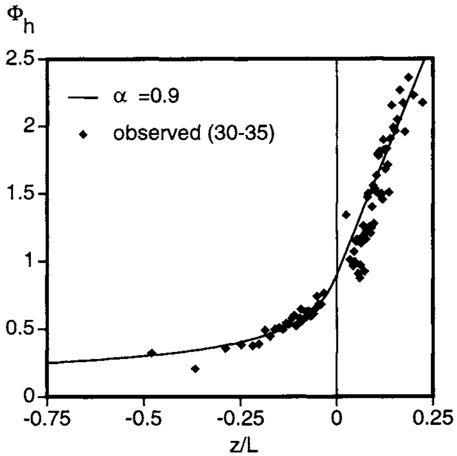

Figure 4. Flux-profile functions Φ_h observed over Speulderbos. The lines indicate the classical functions according to equations (3) and (4) using a value of 0.9 for the correction factor α.

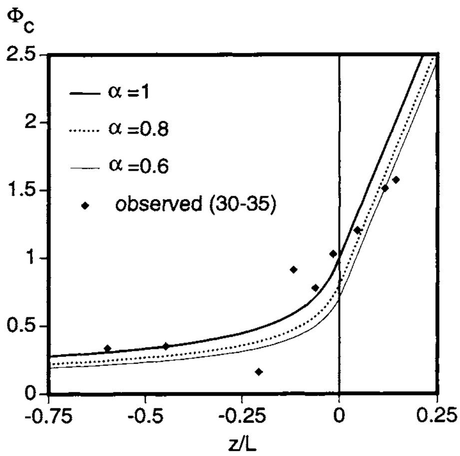

Figure 5. Flux-profile functions Φ_c over Speulderbos. The drawn line indicates classical functions according to equations (3) and (4) using indicated values for α.

The results for ozone for the 30–35 m interval are displayed in Figure 5. The results for this height interval compare reasonably well with the results for this interval for heat. The uncertainty due to scatter however is much larger. For the other height intervals the scatter is even worse. For the interval 24–35 metre the comparison between heat and ozone is quite good. For both O_3 and heat an α factor of 0.75 gives a reasonable fit to the data. It is therefore concluded that there is no significant difference between the functions for heat and those for ozone.

In order to test this assumption further the ozone flux was calculated using the gradient method and compared with fluxes measured by the eddy correlation method. To calculate the gradient flux the flux-profile functions derived for heat (given in Table 1) were used for each of the three height intervals.

The results of this comparison are presented in Figure 6 where the average of the three height intervals is compared with the eddy correlation flux. The observed fluxes compare quite well over a range of a factor of ten. This gives confidence in the flux-profile functions chosen for the analysis. The flux calculated according to the so called modified Bowen ratio method was also compared with the eddy correlation flux. The fluxes calculated for several height intervals also compared very well with the eddy correlation flux [10].

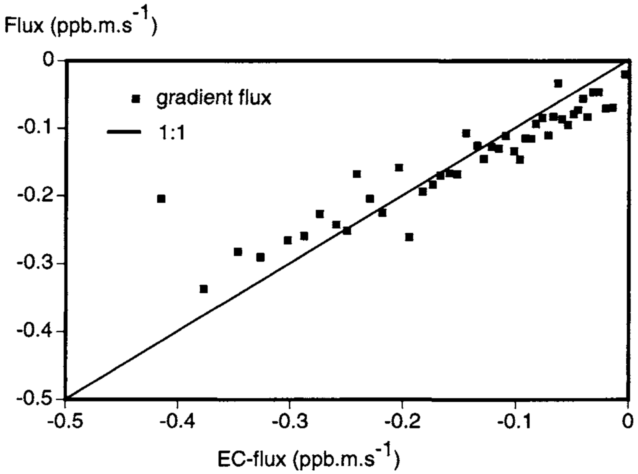

Figure 6. The flux of O_3 to the Speulderbos calculated using the gradient method against the flux observed using the eddy correlation flux.

6. CONCLUDING REMARKS

The Speulderbos area is relatively inhomogeneous. To test the validity of the constant flux assumption over the forest several additional measurements were carried out in a three week campaign in June 1993. The ozone flux was measured by eddy correlation at the 25 m and at 35 m level. No significant differences could be detected between the fluxes of momentum, heat and ozone observed at two levels [18]. During this campaign the ozone flux was recorded simultaneously at a second tower located some 50 m away from the one described here. The fluxes at both towers did not deviate either. Both observations endorse the assumption that a fairly homogeneous flux field exists over Speulderbos. In this experiment the effect of chemical reactions of ozone with nitrogen oxides was also studied. Some of the observed uptake of ozone may be caused by chemical reactions in air between ozone and nitric oxide emitted from the forest floor. This effect will be investigated in more detail.

The experiments shown here form evidence that the gradient (and the Bowen ratio method) can be used over forest for ozone. It seems reasonable to assume that this conclusion is also valid for other trace gases with sinks in the canopy such as sulphur dioxide or ammonia. This conclusion however may not be valid for gases with sources and sinks at the forest floor such as nitrogen oxides.

The flux profile function found in this study can only be applied in Speulderbos. Generalisation of the flux profile functions observed in this study in more general terms such as tree height and density will be attempted in the near future.

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