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Monitoring dry deposition fluxes of SO_2 and NO_2: Analysis of errors

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Abstract

Dry deposition fluxes of acidifying trace gases are continuously determined at two locations in the Netherlands, a low vegetation site and a forest. In this work the errors in determined fluxes and deposition velocities are analysed in detail. The analysis is based on the results of both laboratory and field experiments. The average random error in SO_2 deposition fluxes is 50% for 30-min measuring cycles. Systematic errors are generally limited to 20% (underestimation) and these can be partly reduced by correction procedures. NO_2 fluxes are systematically in error, varying from -50 to +100%, mainly due to interference by O_3 and H_2O and meteorological errors. The random error in the NO_2 fluxes is large (25% to 1000% for 30-min measuring cycles). Despite the large errors, NO_2 deposition velocities determined at a test site showed approximately the same diurnal course as values obtained from a parameterization, which is based on the assumption that the surface exchange of NO_2 is mainly determined by stomatal behaviour.

1. INTRODUCTION

Dry deposition of trace gases and aerosols, particularly sulphur and nitrogen components, leads to soil acidification and eutrophication [1,2]. Despite many studies on dry deposition (e.g. [3,4]) questions still remain with regard to the underlying processes and effects. Systematic and continuous measurement (monitoring) of dry deposition fluxes of acidifying compounds is required to gain more insight and to validate and improve models used to calculate land use specific deposition parameters. Further, trends may be observed and effects of emission reduction programmes can be evaluated.

In the Netherlands, two automatic systems are operated to monitor dry deposition fluxes of SO_2, NH_3 and NO_2, one at a low vegetation site and the other at a forest location. The systems are based on the gradient method. They produce a restricted amount of continuous data and need little maintenance and calibration. The two systems are similar, but not identical. Differences are given in section 2. Detailed descriptions are given in [5,6].

Dry deposition measurements are liable to several errors, which are important to be known in order to derive sufficiently accurate fluxes from measurements. Businger gives a good survey of the different error sources and some correction procedures [7]. Error sources may be instrumental errors (e.g. drift, noise, sensitivity to interfering compounds), errors caused by equipment and system configuration (e.g. adsorption effects in sampling tubes, upward wind distortion) and methodical errors (occurring when requirements with respect to fetch and measuring heights, steady state conditions, chemical reactions, etc., are not met). The latter are difficult to determine. Therefore, only data selected according to criteria based on these requirements are used [4,7,8]. However, elimination of data may also lead to errors in long term average dry deposition fluxes, since the selected periods may not be representative. Erisman *et al.* have developed a procedure to derive general dry deposition parameters from a limited set of selected data [3,8]. He has also estimated the errors caused by this procedure.

In this paper we only deal with errors caused by instruments, equipment and system configuration. We have estimated these errors for our systems, based on results of laboratory tests and field experiments. In the laboratory, the specifications of the trace gas monitors used in the systems were determined. Field measurements were conducted during a test period (December 1991 until August 1992) at the heathland Elspeetsche Veld with the two systems operated side by side. The performance and reliability of both systems were tested. SO_2 fluxes were mutually compared (note: NO_2 fluxes were determined with only one system). Effects of flow distortion by obstacles on wind velocity and momentum flux were studied. Further, eddy correlation measurements of latent heat and NO_2 fluxes were carried out during a few days. These will not be discussed in this work.

The analysis given in this paper is focused on the Elpseetsche Veld experiments and on SO_2 and NO_2. Analogous procedures can be applied for other gases or other sites.

2. THE MONITORING SYSTEMS

2.1 Instruments and equipment

Fig. 1 shows a schematic of one of the systems, when operated during the test period at the heathland Elspeetsche Veld. (Later this system was installed at Speulder forest, where it is still operated nowadays). The low vegetation system is similar, but not identical. Differences are given at the end of this section.

A sonic anemometer (Kayo Denki DAT-310, Japan) is used to measure horizontal and vertical wind velocity, wind direction, friction velocity and heat flux. Its probe is mounted on the top of a slim mast (I) at 5.5 m height. The probe is provided with an inclinometer to measure the deviation of its position to horizontal alignment, and with a rotor to turn its open side towards the wind direction every hour. A net radiation meter (Thies 8110, Germany) and a temperature/relative humidity sensor (Vaisala HMP121B, Finland) are fixed on a small mast (III) at a height of 1.5 and 2 m, respectively.

Air is sampled at a flow rate of 2 l min^{-1} through five 7 m long, isolated FEP Teflon sampling tubes (4 mm i.d.) mounted on 50 cm long outriggers fixed to a slim telescopic mast (II) at a height of 4 m (reference tube) and 4, 2, 1 and 0.5 m (other tubes). The tubes are connected to a valve system in box **B**, with which the gas monitors are supplied either with zero air (ambient air led over an active charcoal filter and a dust filter) for regular zero calibration or with ambient air from the inlets. All tubes are continuously sucked through with a bypass pump, thus maintaining equilibrium inside.

Box A houses two SO_2 and two NO_2 monitors. The SO_2 monitors are Model 43S Pulsed Fluorescence analysers (Thermo Environmental Instruments Inc., USA) and the NO_2 monitors are LMA-3 Luminox analysers (Scintrex Ltd., Canada). For both gases one monitor (called the *reference* monitor) continuously measures the concentration at the reference level (4 m). In this way changes of the gas concentration during a measuring cycle can be measured and corrected for. The other monitor (called the *scanning* monitor) samples consecutively at the various heights to measure the gas concentration gradient. The applied measuring scheme is given in section 2.2. At Elspeetsche Veld the monitors were calibrated at least every two weeks using a Model V3M portable calibrator (Environnement, France) provided with one permeation device for SO_2 and one for NO_2. Zero calibration is performed by the system, as described above. The luminol for the NO_2 monitors was refreshed at least every 2 weeks.

Box C houses the computer, used to control the monitoring system, to collect and store data and to perform necessary calculations The low vegetation system resembles the forest system except that NO_2 is not measured and that a wind vane and a three-cup anemometer are used instead of a sonic anemometer. These are mounted at 5 m height on the mast carrying the sampling tubes (mast I is not used). Friction velocity and sensible heat flux are derived from wind velocity, standard deviation of the wind direction,

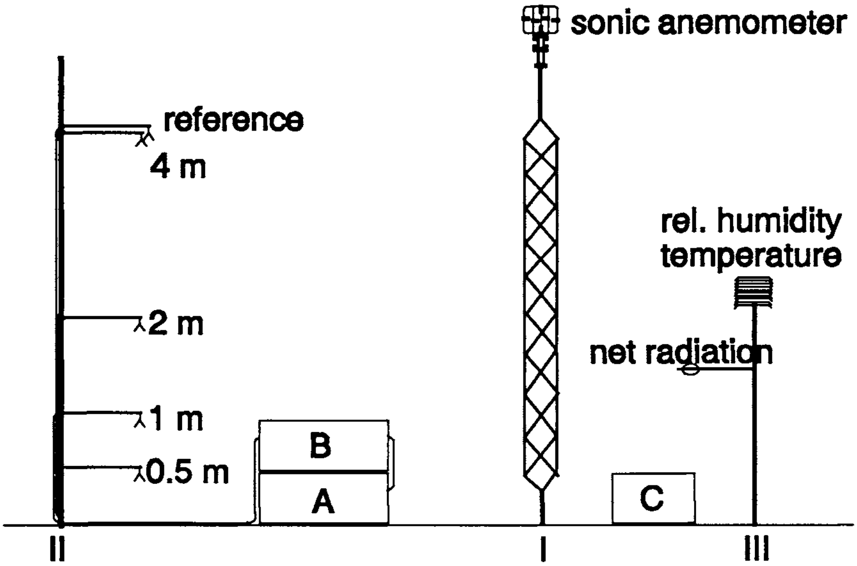

Figure 1. Schematic of the monitoring system at Elspeetsche Veld.

temperature and net radiation using a parameterization [8,9]. Vertical wind velocity is not measured. Further, the low vegetation system contains a surface wetness sensor mounted in the canopy.

During the tests at Elspeetsche Veld masts and boxes were placed in such a way that the ideal fetch was not significantly disturbed and errors introduced by possible inhomogeneities were minimal.

2.2 Measuring scheme

The scheme described below was applied during the Elspeetsche Veld experiments. Measurements are performed in consecutive hourly cycles, consisting of four periods each. During the first period (6 min) zero air is supplied to the monitors in order to determine the zero signal and minimize errors due to zero drift. During the following two periods, each taking 4x6=24 min, gradients of SO_2 and NO_2 are measured. In both periods the scanning monitor measures the concentrations at four levels successively (4, 2, 1 and 0.5 m), whereas the reference monitor measures simultaneously concentrations at the reference level (4 m). In all measurements the monitors are flushed for 5 min with the supplied air, whereafter the signal is sampled for 1 min. During the fourth period (6 min) data are written to disk, the prevailing wind direction is determined and the rotor carrying the sonic anemometer probe is set.

Meteorological parameters are continuously measured during the first three periods (= 54 min) of the cycle; 6-min average values of horizontal and vertical wind velocity, wind direction, friction velocity, heat flux, net radiation, temperature and relative humidity are calculated from the raw data and stored.

3. ERROR ESTIMATIONS

The equations used to calculate dry deposition fluxes from measured data are derived from the work of Hicks *et al.* [10] and are given in [6,8,11]. In this work we only give the essential equations. For simplicity we use two measuring heights (the highest and the lowest) instead of four assuming that gradients are linear. In practice, this assumption must always be checked by using more than two heights, because e.g. the lowest measuring height might be chosen just inside the roughness layer. For NO_2 gradients are often non-linear due to reactions involving NO and O_3. To first order this does not harm the results of our estimations.

The dry deposition flux F (in ppb m s^{-1}) is calculated from the concentration gradient $\partial c/\partial Z$ according to

$$F = -u_*\kappa\frac{\partial c}{\partial Z} \approx -\frac{\kappa u_*\Delta c}{\Delta Z} \qquad (1)$$

where u_* is the friction velocity (in m s^{-1}), c the gas concentration at 4 m (in ppb) and κ the von Karman constant (= 0.41). Because we use two measuring heights, $\partial c/\partial Z$ can be approximated by $\Delta c/\Delta Z$, in which Δc is the difference in concentration between 4 and 0.5 m (in ppb), and ΔZ is given by

$$\Delta Z = \ln\left(\frac{z_1-d}{z_2-d}\right) - \Psi\left(\frac{z_1-d}{L}\right) + \Psi\left(z_2-\frac{d}{L}\right) \tag{2}$$

where z_i is the measuring height, z_0 the roughness length, d the displacement height and L the Monin-Obukhov length (all in m). The dimensionless stability functions ψ are given in [8]. For neutral conditions $\psi = 0$. Since errors in u_* and ΔZ are usually limited to 10 to 20%, as we will show in section 3.3, and Δc is small, the error in F is dominated by the error in Δc. From eq.(1) and

$$F = -v_d c \tag{3}$$

where v_d is the deposition velocity at 4 m (in m s^{-1}), we arrive at

$$\frac{\Delta c}{c} \approx \frac{v_d \Delta Z}{\kappa u_*} \tag{4}$$

With this equation and suitable values for d, z_0, v_d, u_* and c, values of Δc can be calculated. For Elspeetsche Veld the displacement height is 10 cm and the roughness length 4 cm (for wind directions, where the fetch is adequate). Typical values of u_* and v_d, obtained from the measurements during the test period, are given in Table 1. Five classes of stability conditions were defined based on the value of (z-d)/L. Their relative occurrence is also given in Table 1. Further, this table shows the calculated values of Δc for the 50-percentiles of c (1.2 ppb for SO_2 and 10 ppb for NO_2). We used these values to estimate the errors resulting from the behaviour of the gas monitors.

3.1 Gas monitors

Drift, linearity, noise, temperature dependence, sensitivity to interfering components, etc., of the SO_2 and NO_2 monitors were determined in a calibration chamber according to a standard Performance Characteristics procedure [12]. For the most important error

Table 1
Values of relevant parameters used for error estimations

Parameter	very unstable	unstable	neutral	stable	very stable
(z-d)/L	<-0.5	-0.5 - -0.1	-0.1 - 0.1	0.1 - 0.5	>0.5
rel. occurrence (%)	5	11	66	14	4
u_* (m s^{-1})	0.15	0.25	0.4	0.15	0.1
ΔZ (-)	0.94	1.42	2.28	3.68	6.94
v_d SO_2 (cm s^{-1})	0.1-0.7	0.2-1	0.3-3	0.15-0.7	0.05-0.3
v_d NO_2 (cm s^{-1})	0.02-0.3	0.02-0.3	0.01-0.5	0.005-0.1	0.002-0.05
Δc SO_2 (ppt)	20-130	30-170	50-500	100-500	100-600
Δc NO_2 (ppt)	30-400	30-400	20-700	30-600	40-800

sources the results and the corresponding errors in Δc are briefly discussed below. Detailed results and other error sources are given in [6]. Table 2 (see section 4) gives a summary. We note that in all calculations presented below the concentration of a gas is assumed to be constant during one measuring cycle. Periods with rapidly changing concentration are eliminated because of the steady state condition requirement [4,7,8].

Temperature dependence

When sampled air enters the monitors, its temperature quickly takes the temperature inside the box housing the monitors. This implies, that significant errors might be expected, when the temperature inside the box suddenly increases or decreases, which happens sometimes as a result of rapid change in sun radiation at sunset or sunrise.

When the temperature dependence of both the scanning and the reference monitor is exactly the same, the error in Δc is 0. Unfortunately, from the experiments in the calibration chamber the dependence of the four SO_2 monitors was found to vary from 0.03 to 0.12% K^{-1} in the range of 5 to 40°C. The error in Δc per K temperature change can be estimated from

$$err_{\Delta c} \approx \left(1-\frac{c}{\Delta c}\right)\left(\delta_{T,s}-\delta_{T,r}\right) \tag{5}$$

where $\delta_{T,s}$ and $\delta_{T,r}$ are the temperature dependence of the scanning and the reference monitor, respectively. The temperature change within one measuring cycle is usually limited to 3 K. Taking the most extreme values for $\delta_{T,s}$ and $\delta_{T,r}$ found in the laboratory experiments (0.03 and 0.12% K^{-1}), the error in Δc varies from 0.3% to 16% for the cases given in Table 1. According to the manual, a temperature compensation circuit should correct the signal of the Luminox NO_2 monitors for temperature influence. However, we found values for $\delta_{T,s}$ and $\delta_{T,r}$ of -0.3 and -0.15% K^{-1}, respectively, in the range of 5 to 40°C. Hence, the error in Δc varies from 5% to 150%. These large errors can be avoided by keeping the temperature inside the box at a constant value, as is done nowadays at Speulder forest.

We note that for longer periods the average error due to temperature influence is nearly 0, since then temperature increases and decreases counterbalance. However, when studying temperature related processes, systematic errors might be introduced.

Interferences

Sensitivity to other components (interferents) may lead to systematic errors. In general, the concentration measured by a monitor can be expressed as

$$c' = c + (\alpha c + \beta)\, c_I \tag{6}$$

where c is the real concentration, c_I is the concentration of the interfering component and α and β are interference parameters. The first refers to effects, which depend on the concentration of both gas and interferent, such as the quenching effect of humidity in chemiluminescence NO_x monitors. The second refers to effects which only depend on the interferent concentration, such as the influence of all S-containing components on the signal of flame photometers used for measurement of SO_2.

Using eq.(6) for both c and c-Δc and eq.(4) for both the gas and the interferent, we derived

$$err_{\Delta c} \approx \alpha c_I + \left(\alpha + \frac{\beta}{c}\right) \frac{v_d{}^I c_I}{v_d} \tag{7}$$

where the term $\alpha\Delta c_I$ has been neglected. In most cases $\alpha = 0$ and the error reduces to the product of β and the ratio of $v_d c$ of the interferent and the gas, respectively.

Only NO and humidity interfere with the signal of the SO_2 monitors. For NO $\alpha = 0$ and $\beta = 0.024$. NO is sometimes transported towards the soil and sometimes emitted. In both cases the absolute value of v_d for NO is usually much smaller than for SO_2. NO concentrations are generally below 1 ppb, so that the error in Δc due to NO interference is generally smaller than 1%. The humidity interference appeared to be rather complicated. To first order eq.(7) is a good approximation for ambient concentrations of SO_2 and humidity, if α is assumed 0 and $\beta \approx -0.013$ ppb per g m^{-3} H_2O. "Deposition velocities" (quotation-marks are used, since the humidity flux is usually directed upwards) of humidity were estimated from net radiation, sensible heat flux, temperature and relative humidity. Values varied from -0.2 to -1.2 cm s^{-1} for unstable conditions, from -0.05 to -1 cm s^{-1} for neutral conditions and from ≈ 0 to -0.1 cm s^{-1} for stable conditions. Using these values and a humidity concentration of 10 g m^{-3} (~50-percentile), the error in Δc becomes 2 to 20%.

The NO_2 monitors are liable to interference of PAN, O_3 and humidity. The PAN interference was determined by others [13,14] to be 25% ($\alpha = 0$, $\beta = 0.25$). PAN concentrations and its v_d values are usually very low [15] and the error in Δc is therefore less than 2%. For the humidity interference we found $\alpha = 0.004$ and $\beta = 0$. With the v_d values and concentration of H_2O given above, the error in Δc becomes 10 to 25%. From our interference experiments with O_3 we found $\alpha \approx -0.001$ and $\beta \approx 0.01$. These values are considerably higher than found by others [13,14]. With our experimental values the error in Δc is highly dependent on NO_2 and O_3 concentrations and varies between -25% to +100%. However, if results of others are used for α and β, much smaller errors are obtained. This must be further investigated.

Noise

Noise leads to random errors in measured concentrations. Suppose that the random error in c due to noise is σ_c. Because of its random character the error in Δc is about $\sqrt{2}$ times as large. Since the concentrations measured by the scanning monitor are corrected by those measure with the reference monitor, the error in Δc will be given by

$$\sigma_{\Delta c} \approx 2\sigma_c \tag{8}$$

Noise was determined as the standard deviation in the measured signal (1-min average values), when a constant concentration was supplied to the instruments. For the SO_2 monitors $\sigma_{\Delta c} \approx 70$ ppt at the 50-percentile (c = 1.2 ppb). Hence, the error in Δc varies from ca. 10% at very stable conditions with high v_d to 300% at very unstable conditions with low v_d. At neutral conditions, which occur most of the time, with $v_d = 1$ cm s^{-1} (average value), the error is nearly 50%. For NO_2 $\sigma_{\Delta c} \approx 180$ ppt at the 50-percentile (c = 10 ppb) and the error in Δc varies from about 25% at very stable conditions with high v_d to nearly 1000% at conditions with very low v_d, usually occurring at night, when the stomata are closed. At neutral conditions with v_d = 0.1 cm s^{-1} (average value), the error is about 130%.

Other errors

Errors due to drift, alinearity and response time were small. Drift is <0.1% day^{-1} or <0.1 ppt cycle^{-1} for the SO_2 monitors and even less for NO_2. The SO_2 monitors were linear within 1% in the range used in the system (0-50 ppb). The NO_2 monitors show strong alinear behaviour below 4 ppb and above ca. 20 ppb. Between these concentrations linearity is better than 1.5%. Below 4 ppb the calibration curve shows a dip; at c = 1.6 ppb deviation from linearity is 35%. Above 20 ppb the curve shows a downward bend and deviation from linearity rapidly increases with increasing concentration. For practical reasons the whole calibration curve cannot be regularly checked in the field. Therefore, only data between 4 and 20 ppb are selected for calculation of gradients. We note that this range covers nearly 70% of the entire range of concentrations at Elspeetsche Veld.

The response times (100 s for the SO_2 monitors and 1 s for the NO_2 monitors at 95% of the total concentration change) are sufficient, since during all measurements the monitors are flushed for 5 min before signal sampling (see section 2.2).

Summary

Table 2 gives a summary of errors in gradients resulting from the behaviour of the gas monitors and the sampling equipment. The latter will be discussed in the next section.

3.2 Errors caused by sampling equipment

Because all parts of the sampling equipment (tubes, valves, couplers) are made of FEP Teflon, reactions of SO_2 and NO_2 with the tube walls are not expected. Forming of water layers on the tube walls, in which the gases may dissolve, as a result of condensation is

Table 2
Summary of estimated errors in Δc values for SO_2 and NO_2 (in %)

Parameter	error type	error in Δc (SO_2)	error in Δc (NO_2)
linearity	systematic	<2	<3
drift	systematic	<0.5	<0.5
temperature dependence	systematic$^{1)}$	0.3 - 16	5 - 150
interference by H_2O	systematic	2 - 20	10 - 25
interference by NO	systematic	<1	-
interference by O_3	systematic	-	-25 - +100
interference by PAN	systematic	-	<2
noise	random	10 - 300	25 - 1000
sampling tubes	systematic	≈0	<5

[1)] Worst case situation. Errors are usually smaller. For long term average fluces the errors are nearly 0 (see section 3.1).

prevented as much as possible by isolation of the tubes. We checked this by several field experiments, e.g. by comparing concentrations measured by both SO_2 and NO_2 monitors connected to the same sampling tube (using a FEP Teflon tee just in front of the monitor inlets), and connected to different tubes with their inlets both at 4 m height. No differences were found, implying that adsorption effects are negligibly small.

The photochemical equilibrium involving NO, NO_2 and O3 will be disturbed inside the isolated, dark sampling tubes. There, NO_2 is still formed from NO and O_3, whereas the photochemical conversion of NO_2 into NO and O_3 stops. This results in a net NO_2 production, which can be estimated with the following equation derived by Beier en Schneewind [16] for short residence times in tubes

$$\Delta [NO_2] \approx k [NO] [O_3] \Delta t \tag{9}$$

in which $\Delta[NO_2]$ is the net NO_2-production (in ppb), k the reaction constant for the production of NO_2 from NO and O_3, Δt the residence time in the tube (2.6 s at Elspeetsche Veld) and [NO] en $[O_3]$ the equilibrium concentrations in the air (in ppb). The reaction constant varies from 2.5×10^{-4} tot 4.5×10^{-4} ppb^{-1} s^{-1} depending on air temperature and pressure. We estimated $\Delta[NO_2]$ using 50-percentiles of NO and O_3 concentrations measured at nearby locations of the National Air Quality Monitoring Network (ca. 1 and 30 ppb, respectively) to be 35 ppt. Because NO and O_3 show complementary behaviour, higher values will scarcely occur. The error due to the difference in net NO_2 production at both measuring heights was determined analogously to the interference calculations. It was found to be less than 5%.

3.3 Errors in meteorological parameters

According to eqs.(1) to (3) F depends on u_* and ΔZ, which on its turn depends on u_*, T and the sensible heat flux H_0. The uncertainty in u_* and H_0 was determined by comparing values obtained with the two systems. For u_* the linear regression slope was 1.05 and the intercept did not significantly deviate from 0; the correlation coefficient was 0.983 and the standard deviation of points around the regression line was 0.03 m s^{-1}. These results fairly agree with those of Erisman and Duyzer [17]. From the comparison we concluded that the random error in u_* is less than 0.03 m s^{-1} or 10%. However, systematic errors cannot be detected in this way. From the work of Moore, Zeller *et al.*, Dillmann [18-20] and our own flow distortion experiments [6], it appears that u_* values measured with the sonic anemometer in our system are underestimated by 8 to 12% due to sampling errors, response characteristics and flow distortion. Since the parameterisation yields approximately the same u_* values, their systematic error is about the same.

For H_0 the agreement between measured and parameterized values was good for fluxes between -100 and 150 W m^{-2}, as had also been found by Erisman and Duyzer [17]. Random differences are about 15%. At higher H_0, the parameterized values are underestimated by 20%. Depending on atmospheric stability, the systematic error in H_0 values measured with a sonic anemometer may be -10 to 10% due to sampling errors, response characteristics [18,19] as well as flow distortion [6] and neglection of terms in the calculation of temperature fluctuations [21].

Errors in $u_*/\Delta Z$ were estimated using data measured at Elspeetsche Veld for several stability conditions and the errors in u_* and H_0 just given (the influence of T was neglected). These estimations yielded systematic underestimations of 5% at unstable, 10%

at neutral and 15% at stable conditions. Random errors of 10% (unstable, neutral conditions) and 20% (stable conditions) must be added to these values.

Other meteorological parameters, which are measured in the systems (net radiation, relative humidity, temperature, wind velocity and wind direction) are used either as input for the parameterization or for process study and data selection. For that purpose the specified accuracy of the instruments is sufficient [6]. For all parameters values measured by similar instruments of both systems at Elspeetsche Veld showed good agreement and specified accuracies were confirmed.

3.4 Field intercomparison

SO_2 deposition fluxes and velocities measured simultaneously with both systems at Elspeetsche Veld were mutually compared. Fig. 2 shows the course of v_d obtained with both systems during 4 days in April 1992, when nearly all measurements standed the selection criteria (see section 1). Except for a few cycles the agreement is good. The average v_d values, both for this 4-days period and for all cycles selected from the whole test period at Elspeetsche Veld, did not systematically differ. The random uncertainty in v_d was estimated from the root mean square difference between v_d values to be ca. 75% for a 30-min cycle. This value is comparable to those obtained from the estimations in sections 3.1 and 3.3 with respect to random error sources. Estimated systematic errors could not be verified in this way.

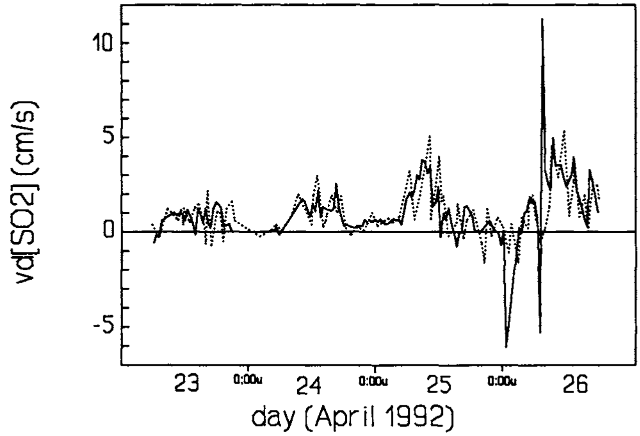

Figure 2. Course of the SO_2 dry deposition velocity (cm s^{-1}) measured with the two monitoring systems (indicated with full and dotted line, resp.) at Elspeetsche Veld.

NO_2 fluxes determined from the gradient measurements at Elspeetsche Veld were compared to those obtained from a parameterisation, in which the NO_2 surface resistance is assumed to be equal to the stomatal resistance. Despite the large errors in NO_2 gradients, the agreement was fair. At night, the measured values were somewhat higher (measured and parameterised v_d values were 0.07 and ≈0 cm s^{-1}, respectively) and during daytime they were slightly lower (0.2 and 0.3 cm s^{-1}).

4. CONCLUSIONS

Errors in SO_2 and NO_2 dry deposition fluxes determined with a monitoring system based on the gradient method were analysed in detail.

Instrumental noise is the dominating random error source. The estimated errors in concentration gradients due to noise were 10 to 300% for SO_2 and 25 to 1000% for NO_2, depending on meteorological and surface conditions. At neutral conditions, which occur more than 60% of the time, these errors are ca. 50 (SO_2) and 130% (NO_2), respectively, for average v_d values. Random errors in the ratio of u_* and the stability corrected logarithmic height difference ΔZ are 10 (neutral, unstable) to 20% (stable conditions). For SO_2 estimated errors were comparable to the root-mean-square difference between v_d values simultaneously determined with both systems at the heathland Elspeetsche Veld. We note that due to its random character the error in long term average fluxes will be small. However, for process studies (e.g. determination of daily course; study of relationship between fluxes and other parameters) errors may still be large, if the number of selected measurements is too small. This implies that such studies must be done carefully.

At rapidly increasing temperature inside the box housing the gas monitors, significant errors occur due to temperature dependence of the monitors. Such errors can be minimized by keeping the temperature inside the box at a constant level, as is done nowadays in the system at Speulder forest.

Significant systematic errors are caused by some interfering components. For the SO_2 monitors humidity interference causes errors of 2 to 20% (underestimation) at unstable to stable conditions, respectively. For the NO_2 monitors O_3 and humidity interference cause errors of -25 to +100% and -10 to -25%, respectively. Systematic underestimations in F resulting from errors in meteorological parameters (u_* and H_o) are 5% at unstable, 10% at neutral and 15% at stable conditions. Other systematic errors (due to drift, alinearity, other interfering components, sampling equipment) are smaller than 5%. Because systematic errors depend on several conditions, such as atmospheric stability, concentrations of interfering components and correlations between them, the impact on long term average SO_2 and NO_2 fluxes is difficult to determine. However, for SO_2 we may conclude that systematic errors are generally lower than 20%. For NO_2 such a general statement cannot be made. It is better to correct fluxes for systematic errors. This can be partly done for errors in u_* and H_0 (and hence ΔZ) by applying procedures proposed by Moore [18] and Zeller *et al.* [19]. Corrections for interferences can be made by applying the equations presented in this work and concentrations and deposition velocities of the interfering components. The latter should preferably be measured, but this is not always possible. However, estimations of these values are sufficient for first-order corrections. For example, humidity concentrations and v_d values can be well estimated from temperature, relative humidity, net radiation and sensible heat flux, which are all measured by our systems.

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