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The precision and spatial variability of some meteorological parameters needed to determine vertical fluxes of air constituents

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Abstract

Measurements of meteorological parameters are normally reduced to one set of instruments without replication. If the data are used to generate flux data for the modelling of momentum, heat and matter fluxes between atmosphere and vegetation, the order of magnitude of errors has to be known. Errors arise both from the fact that many instruments are not calibrated individually, as well as from patchiness of vegetation and soil even in ecotopes which are normally considered horizontally homogeneous. In order to quantify the overall errors, experiments were performed with sets of equal or similar instruments whose results were compared under otherwise identical conditions. We concluded that for wind velocities, an overall error *e* of 0.1 $m \cdot s^{-1}$ should be assumed for high resolution cup anemometers; 0.2 $m \cdot s^{-1}$ are adequate for standard instrumentation. Vertical gradients of wind velocities near the canopy can be resolved with a precision of 15 to 20 %. Air temperature measurements are normally performed using instrumentation with a (nominal) resolution of 0.1 K. Air temperature measurements are much more sensitive against spatial inhomogeneities of the canopy than wind velocity measurements. Air temperature gradients require a resolution of 0.01 K which presupposes careful intercalibration of the sensors. The potential to establish air temperature gradients in one location must not lead to the conclusion that these measurements are representative in space; the gradients assessed are in the order of magnitude of the errors, especially at noon. Measurements of relative air humidity are afflicted with an error of 2 %. For precipitation measurements, the overall error is in the order of 0.1 mm per half hour or 5 to 10 % for monthly sampling, provided that a flow distortion correction has been performed. Even measurements of entities which are independent of the patchiness of the plant/soil system such as global radiation are not necessarily representative in space if one sensor only is exposed.

Key words: radiation, wind velocity, air temperature, precipitation, data quality

Zusammenfassung

Die Genauigkeit und räumliche Variabilität einiger meteorologischer Größen zur Bestimmung vertikaler Flüsse von Luftinhaltsstoffen

Es ist üblich, meteorologische Datensätze mit jeweils einem Sensor ohne Wiederholung zu messen. Wenn so erzeugte Daten zur Berechnung von Flüssen im Rahmen einer Modellierung von Impuls-, Wärme- und Stoffflüssen verwendet werden, sollte die Größenordnung der Fehler bekannt sein. Fehler ergeben sich sowohl aus dem Umstand, dass viele Instrumente nicht individuell geeicht sind, als auch daraus, dass die Vegetation auch in Ökotopen (für die normalerweise horizontale Homogenität vorausgesetzt wird) „fleckig“ ist. Um den Gesamtfehler solcher Messungen abzuschätzen, haben wir Parallelmessungen mit mehreren gleichen oder ähnlichen Sensoren unter sonst gleichen Bedingungen durchgeführt und die Ergebnisse verglichen. Wir schlossen, dass für die Bestimmung von Windgeschwindigkeiten mit hochauflösenden Schalenkreuzanemometern ein Gesamtfehler von 0,1 $m \cdot s^{-1}$ anzunehmen ist, mit Standard-Messgeräten einer von 0,2 $m \cdot s^{-1}$. Vertikale Gradienten der Windgeschwindigkeit lassen sich in Bodennähe mit einer Genauigkeit von 15 bis 20 % bestimmen. Lufttemperaturmessungen werden normalerweise mit Sensoren durchgeführt, die eine (angegebene) Auflösung von 0,1 K aufweisen. Lufttemperaturmessungen reagieren deutlich empfindlicher auf Bestandesinhomogenitäten als Windgeschwindigkeitsmessungen. Die Bestimmung von Lufttemperaturgradienten erfordert eine Auflösung von mindestens 0,01 K. Dies setzt eine sorgfältige Interkalibrierung der Sensoren voraus. Die Möglichkeit der Bestimmung von Gradienten an einem Ort kann nicht darüber hinwegtäuschen, dass diese Messungen nicht örtlich repräsentativ sind und die gemessenen Gradienten sich insbesondere am Mittag im Bereich der Fehler bewegen. Messungen der relativen Luftfeuchte sind mit einem Fehler von 2 % behaftet. Für die Bestimmung der Niederschlagsmenge ist bei Halbstundenwerten mit einem Fehler von 0,1 mm zu rechnen. Bei Monatsproben beträgt der Fehler 5 bis 10 %, sofern eine Korrektur des Überströmungsfehlers vorgenommen wurde. Selbst Messungen von Größen, die von der “Fleckigkeit” der Bestände unabhängig sind, wie die Globalstrahlung, sind nicht notwendigerweise flächenrepräsentativ, sofern man nur einen Sensor einsetzt.

Schlüsselworte: Strahlung, Windgeschwindigkeit, Lufttemperatur, Niederschlag, Datenqualität

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1 Introduction

Interrelations between the elements of the climate system consist of fluxes of energy and matter between these elements. As these fluxes cannot be assessed by measurements, area wide models have to be applied to quantify them. These models have to be calibrated as well as validated at well established measurements sites. The sites where the exchange of energy and matter between the atmosphere near the ground and the respective plant/soil system is studied have to be equipped with micrometeorological instrumentation. The fluxes obtained are prerequisite for the establishment of dose-response relationships (Dämmgen et al., 1993, 1997).

The modelling with micrometeorological approaches of vertical fluxes of air constituents between the atmosphere and vegetation presupposes ground based measurements of meteorological parameters and concentrations of the species under investigation. In principle, flux gradient relationships established for special sites at field level have to be extrapolated to large areas (inferential modelling). Thus both the flux gradient relationships as well as the meteorological parameters have to be representative of the ecosystem considered. In addition, vertical fluxes of momentum, heat or matter can be determined with micrometeorological techniques, if the atmospheric surface layer is stationary and horizontally homogeneous. In principle, these marginal conditions have to be met for each data set. In this surface layer, a sensor records information which arises from its footprint area. However, the information obtained from a single sensor at some height above the ecosystem has to be representative of the whole system and this system only. The representativeness and the precision of this information is not only depending on the quality of the sensor, but also of properties of the atmosphere and the plant/soil system.

While stationarity is primarily a property of the atmosphere (and not of the respective plant/soil system), horizontal homogeneity is a function of the variability of source and sink properties of the phytosphere including its horizontal extension (fetch). Suitable tools to estimate whether or not the information collected by a sensor is representing the properties of the system, are the two dimensional source-area approach (cf Schmid, 1994) or the one-dimensional footprint approach (e.g. Horst and Weil, 1992; Horst, 1999; Haenel and Grünhage, 1999; Kormann and Meixner, 2001). Horizontal homogeneity of the plant/soil system means that patchiness is not existent or irrelevant. However, all real ecosystems including agricultural mono-cultures are patchy to some extent. In such cases, measurements of micrometeorological entities are unlikely to be representative of the whole system.

Vertical fluxes can be determined directly using eddy covariance techniques with an adequate resolution in time. "Indirect" experimental methods derive fluxes from the gradients of horizontal wind velocity, air temperature and air constituent concentrations including tracer concentrations. Soil-Vegetation-Atmosphere-Transfer (SVAT) models require a minimum set of meteorological parameters, such as radiation, horizontal wind velocity, air temperature and humidity and concentrations of air constituents. (For a summary see e.g. Grünhage et al., 2000). Both indirect measurements as well as models require data sets with known precision for error propagation calculations which are an integral element of quality assessment.

Normally, atmospheric properties are determined using single sets of standard instruments which are bought as calibrated systems with documented accuracy (*trueness*). Each single instrument is part of a pool of instruments for which *typical* properties have been derived. As a rule, the single sensor itself is not calibrated. Therefore, it may be inadequate to use standard errors derived from calibration procedures in error estimation or propagation procedures for quality assessment and control.

In principle, patchiness can result in biased (systematic error) as well as in scattered results (random error). The latter may be stochastic in practice due to the properties of the turbulent atmosphere: the mean values (e.g. 10 to 30 minute means) are "sampled" from a whole multitude of different sectors of the plant/soil system, i.e. of different patches.

This paper aims at a quantification of total errors which are likely to influence the assessment of fluxes, in particular with the influence of horizontal patchiness (of the field or the sky) on single point measurements of meteorological parameters and vertical fluxes. It also considers the precision of sensors. The discussion will not focus on calibration derived accuracy, but rather on experience derived from field measurements under "rough" conditions (not repeatability conditions) from the aspect of their applicability in energy and matter flux modelling.

The precision of bulk deposition measurements was subject of earlier publications (Dämmgen et al., 2000, 2005). Preliminary results of a field intercomparison of momentum and sensible heat flux measurements were published in Dämmgen et al. (2002), of latent heat and carbon dioxide flux density assessments in Schaaf et al. (2005).

2 Locations and instrumentation

The experiments were conducted above an extensively managed semi-natural grassland ecosystem and an arable field with crop rotation. The grassland site is located at the Environmental Monitoring and Climate Impact Research Station Linden near Giessen (50°32'N 8°41.3'E, 172 m asl), operated by the Institute for Plant Ecology, University of Giessen, and the Hessian Agency for Environment and Geology. The arable site is part of the Braunschweig Carbon Experiment site at the Federal Agricultural

Research Centre (FAL) west of Braunschweig (52°18'N 10°26'E, 79 m asl). For details see Grünhage et al. (1996) and Jäger et al. (2003) as well as Weigel and Dämmgen (2000).

The instrumentation referred to in this paper is listed in Table 1. Half hourly means are used throughout.

The characterization of errors makes use of the following relations.

(1) For pairs of sensors, the error is described as deviation from the mean.

(2) For a set of sensors (n > 2), the relative mean standard deviation *RSTD* is defined as:

$$RSTD = \frac{\overline{\sigma\,(A_{\text{all sensors, i}})}}{\overline{A_{\text{mean of all sensors, i}}}} \cdot 100 \quad (\%)$$

with

σ the standard deviation of a random sample,

A a sensor signal and i is the measurement period.

Overlining denotes averaging.

(3) The relative stochastic error e of a set of sensors is derived from the standard deviation σ and the overall mean as:

$$e = \frac{\sigma\,(A_{\text{mean of a set of sensors, i}} - A_{\text{mean of all sensors, i}})}{\overline{A_{\text{mean of all sensors, i}}}} \cdot 100$$

(4) A systematic error (bias, B) can be detected by linear regression analysis: the slope deviates from one and/or the intercept is not equal zero. This valuation can be used only, if R^2 is close to 1. At the same time R^2 is a measure for the stochastic error.

Table 1:
Instrumentation used in the comparisons, types, replications and resolution.

	FAL			Linden		
	type	replicates	resolution/ accuracy	type	replicates	resolution/ accuracy
global radiation				Kipp & Zonen Albedometer CM 7B Kipp & Zonen Pyranometer CM 6B Kipp & Zonen CNR 1	1 3 1	
air temperature	Thies Pt100 1/3 DIN	3 gradients	± 0.1 K	Thies Pt100 1/10 DIN (selected)	2 gradients	± 0.01 K
horizontal wind velocity gradients				Siggelkow LISA	2 gradients	recording < 0.1 m·s^{-1}
relative humidity				Vaisala HMP35D Thies Assmann	1 1	± 1–2 % ± 0.15 K
precipitation				Thies Hellmann with tipping bucket Friedrichs Hellmann with collection can Lambrecht Hellmann with collection can Rotenkamp	2 1 1 12	0.1 mm 0.1 mm 0.1 mm 1 month

3 Parameters used in flux assessments

3.1 Global radiation

Five global radiation sensors (see Table 1) which were bought as calibrated systems were mounted above a semi-natural grassland system within an area of 2 ha. The coefficient of determination for the regression of single sensors against the mean of all sensor range between 0.98 and 1.00 which is to be expected. The slope varies between 0.98 and 1.02, the intercept is always negligible (-4 to 4 $W{\cdot}m^{-2}$).

For error propagation calculation a *systematic error* in the order of magnitude of 2 % should be assumed if one relies on one instrument only.

Fig. 1 illustrates that deviations from the spatially representative radiation are generally low, i.e., approx. 50 % of all data sets show a standard deviation of less than 10 $W{\cdot}m^{-2}$ (cf Grünhage and Haenel, 2001). The relative stochastic error *e* of the set of sensors ranged from 2 to 11 % for single sensors. This patchiness can be explained by shading from clouds. The resulting relative mean standard deviation *RSTD* of the whole data set is approx. 6 % without a diurnal variation (between 9 am and 4 pm). Single measurements do not and cannot meet the requirements of a representative parameterization. If the measurement cannot be replicated adequately, it seems adequate to assume a mean stochastic and total error for global radiation measurements of approx. 5 %. The German standard VDI 3786 part 5 (1986) does not inform about typical errors.

For error propagation calculations an *overall error* in the order of magnitude of 2 % should be assumed if one relies on one instrument only.

3.2 Wind velocity and wind velocity gradients

According to German standard VDI 3786 part 2 (2000) turbulence will not be fully developed when the 10-min average of horizontal wind velocity u is less than 1 $m{\cdot}s^{-1}$ at z = 10 m above ground. In these cases, “the applicability of standardised dispersion/deposition/emission models is no longer ensured”. Also, measurement uncertainties for standard equipment have to fall below 0.2 $m{\cdot}s^{-1}$, for the measurements of vertical gradients below 0.1 $m{\cdot}s^{-1}$ (German standard VDI 3786 part 2, 2000).

We investigated wind profile measurements from two sets of 3 LISA wind velocity sensors with magnetic bearings (see Table 1) approx. 20 m apart. Fig. 2 underlines that the absolute deviation of horizontal wind velocity difference is small and independent of height: 89 % of all data sets show a deviation less than 0.1 $m{\cdot}s^{-1}$, 62 % a deviation of less than 0.05 $m{\cdot}s^{-1}$. Patchiness does obviously not influence wind velocity measurements. Linear regression analyses show that these small deviations are systematic rather than stochastic.

For error propagation procedures, we recommend to use an *absolute error* of 0.1 $m{\cdot}s^{-1}$ with high resolution wind velocity sensors such as LISA and of 0.2 $m{\cdot}s^{-1}$ for standard equipment.

With two sensors mounted at z = 3 m and at z = 1.2 m above ground, respectively, four combinations of vertical wind velocity gradients can be evaluated. The whole data set then comprises approx. 27500 combinations forming four coherent sets, respectively. For these sets the standard deviations were analysed (Table 2): for the whole data set approx. 60 % of the standard deviations fall below 0.1 $m{\cdot}s^{-1}$ and 80 to 90 % below 0.2 $m{\cdot}s^{-1}$. A classification by wind velocity at z = 3 m and by vertical gradi-

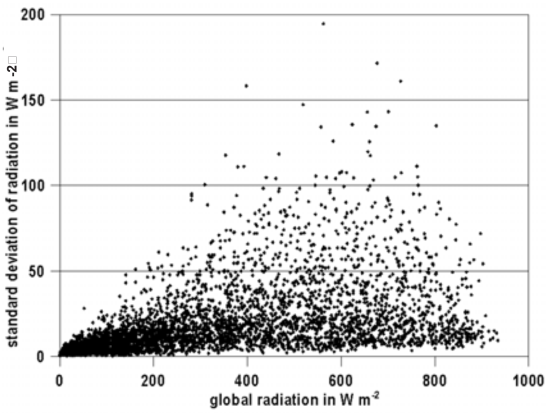

Fig. 1:
Standard deviations of 5 global radiation sensors distributed randomly at z = 2 m above ground (Linden, May to September; n = 4613; half-hourly means).

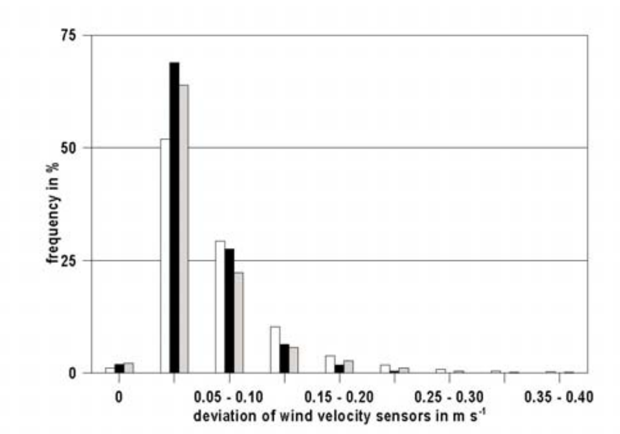

Fig. 2:
Absolute deviations between 2 horizontal wind velocity sensors recorded simultaneously at three heights above ground (Linden, May to September; half-hourly means. Left bar: z = 3 m; centre bar: z = 2.0 m; right bar: z = 1.2 m).

Table 2:
Standard deviations of horizontal wind velocity difference Δu between $z_1 = 1.2$ m and $z_2 = 3.0$ m (May to September; half-hourly means; 4 sensor combinations).

Δu ($m \cdot s^{-1}$)	n	frequency (in %) standard deviation (in $m \cdot s^{-1}$)						
		< 0.1	0.1-0.2	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	> 0.6
u at *z* = 3.0 m above ground : ≥ 1 $m \cdot s^{-1}$								
> 1.5	198	15.7	26.3	22.7	10.6	1.5	6.6	16.7
1.0-1.5	650	40.9	34.6	14.9	4.2	0.8	1.5	3.1
0.5-1.0	1884	57.0	31.8	7.5	2.1	1.2	0.3	0.0
< 0.5	1266	60.6	21.4	10.9	5.4	1.6	0.2	0.0
u at *z* = 3.0 m above ground : < 1 $m \cdot s^{-1}$								
0.5-1.0	125	60.0	30.4	8.0	0.8	0.8	0.0	0.0
< 0.5	2744	76.5	22.4	0.9	0.1	0.0	0.0	0.0
All data	6867	62.8	26.2	6.7	2.3	0.8	0.5	0.8

ents shows that the mean deviation of the gradient increases with the gradient.

The overall relative mean standard deviation is in the order of magnitude of 20 %, for gradients > 1 $m \cdot s^{-1}$ it is about 15 %.

This is in accordance with findings that a single profile tower normally produces adequate wind velocity gradients for the establishment of fluxes of momentum (Grünhage et al., 1994).

3.3 Air temperatures and temperature gradients

At the Linden site, two sets of temperature gradients were obtained in a configuration similar to the wind profile measurements. Two sets obtained with sensors with a nominal resolution 0.01 K were compared (Fig. 3). In contrast to the wind velocities the absolute deviation of horizontal air temperatures is height dependent. Whereas no difference can be detected between measurements at $z = 3$ m and $z = 2$ m, the measurements of $z = 1.2$ m can only be explained by patchiness in the evapotranspiration dynamics of the canopy. Obviously, the sensors mounted at higher elevations above the canopy integrate over "many" patches, sensors mounted closer to the canopy depict a smaller part of the ecosystem containing few or single patches.

A second experiment was performed at Braunschweig over four fortnights. Six standard sensors with a nominal resolution of 0.1 K were mounted in one location at one height as bought, and subsequently after careful intercalibration. In a third step, they were mounted at two heights but still in one location. Finally, three sets of single gradients were measured approx. 10 m apart. Fig. 4 shows the frequency distribution of three pairs of non-intercalibrated replicates at $z = 2.5$ m (i.e. $\Delta z = 0$ m), Fig. 5 illustrates the effects of intercalibration: the Linden sensors and the calibrated Braunschweig sensors behave similarly.

In gradient measurements with three replications at a single location with $\Delta z = 1.5$ m the standard deviation is doubled as expected (Fig. 6). Separation of the three pairs results in a significant broadening of the frequency distribution which clearly depicts the influence of patchiness (Fig. 7), too. Because the absolute gradients are generally small (Fig. 8) single gradient measurements are no adequate tool to describe the properties of the whole system.

Vertical temperature differences exhibit considerable standard deviations which must be attributed to the spatial variability of air temperature at the lowest height ($z = 1.2$ m).

The analysis of the gradients measured at Linden (Table 3) proves that there is no difference in frequency distribu-

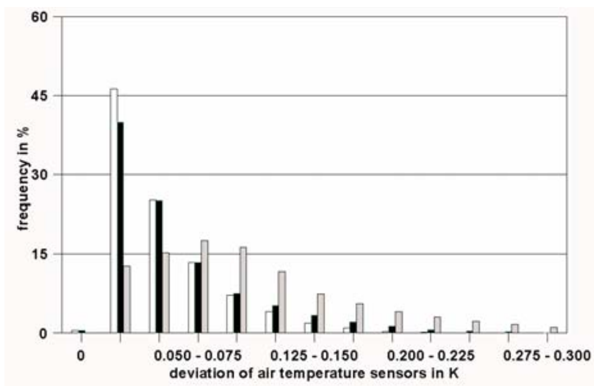

Fig. 3:
Absolute deviations between 2 ventilated and intercalibrated resistance thermometers (nominal resolution 0.01 K) recorded simultaneously at three heights above ground (Linden, May to September; half-hourly means. Left bar: $z = 3$ m; centre bar: $z = 2.0$ m; right bar: $z = 1.2$ m).

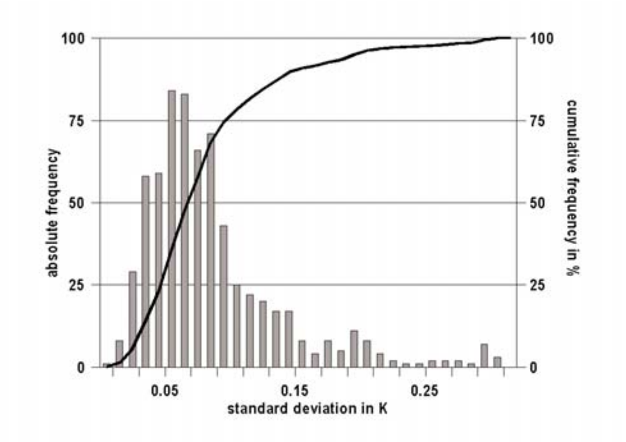

Fig. 4:
Absolute and cumulative frequency distribution of standard deviations of air temperature measurements. FAL. 3 sensors as bought, 1 location, z = 2.5 m. 670 half hourly data sets.

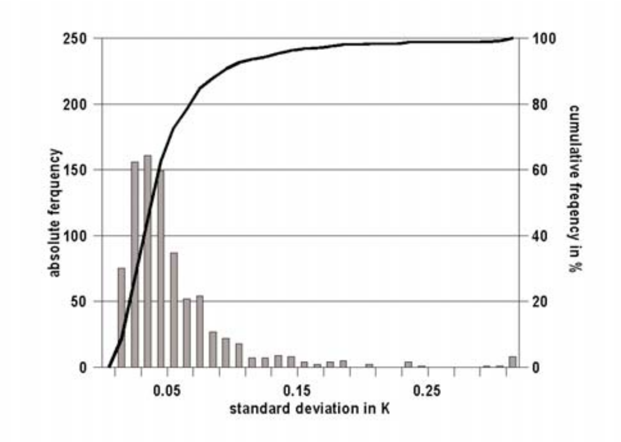

Fig. 6:
Absolute and cumulative frequency distribution of standard deviations of temperature gradient measurements. FAL, 3 pairs of intercalibrated sensors, 1 location, z_1 = 2.5 m, z_2 = 1.0 m, 860 half hourly data sets.

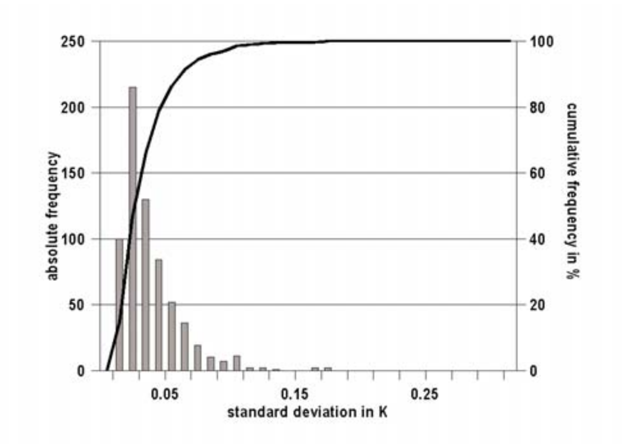

Fig. 5:
Absolute and cumulative frequency distribution of standard deviations of air temperature measurements. FAL. 3 intercalibrated sensors, 1 location, z = 2.5 m. 670 half hourly data sets.

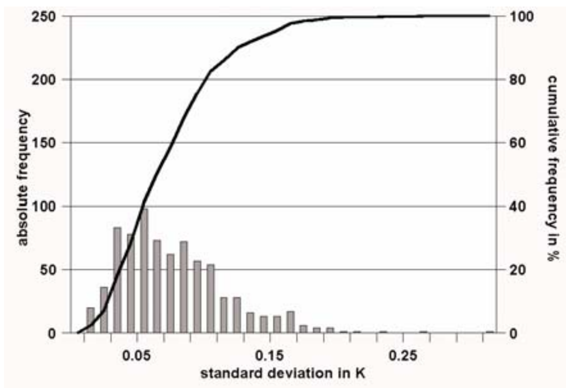

Fig. 7:
Absolute and cumulative frequency distribution of standard deviations of temperature gradient measurements. FAL, 3 pairs of intercalibrated sensors, 3 locations, 10 m apart, z_1 = 2.5 m, z_2 = 1.0 m, 756 half hourly data sets.

tions of standard deviations between stable and unstable atmospheric stratification. During daytime (negative gradients) the absolute temperature gradients are normally small and fall below 0.5 K per 2 m (Fig. 8). Only approx. 40 % of all daytime gradients can be measured with an adequate resolution and an error below 20 %.

In summary, single measurements of vertical air temperature gradients are totally inadequate for daytime measurements. The assumption that the ratio of vertical fluxes of a trace gas F_{cA} and sensible heat F_h are proportional to the driving forces (concentration and temperature gradients)

$$\frac{F_{cA}}{F_h} = \frac{\Delta c_A}{\Delta T}$$

which is consistent in principle (Dämmgen et al, 1997), cannot be used due to inadequate temperature gradient measurements especially during unstable conditions.

3.4 *Relative air humidity*

According to German standard VDI 3786 part 13 (1993) the sensors “must cover 25 to 100 % relative humidity, with an error of less than 5 percentage points”. An intercomparison of an aspirated psychrometer and a well shielded lithium chloride hygrometer (German standard VDI 3786 part 4, 1985) - both instruments are reported to have almost identical characteristics - showed a coefficient of determination (R^2) of 0.998. Compared to the mean, the slopes were 0.975 for the psychrometer and 1.025 the LiCl sensor, with a small intercept of + and

Table 3:
Standard deviations of temperature difference ΔT between z_1 = 1.2 m and z_2 = 3.0 m. (May to September 1999; half-hourly means; 4 sensor combinations).

ΔT (K)	n	frequency (in %) standard deviation (in K)						
		0-0.05	0.05-0.10	0.10-0.15	0.15-0.20	0.20-0.30	0.30-0.40	0.40-0.60
> 2	110	0.9	6.4	18.2	19.1	30.9	13.6	10.9
1.0-2.0	646	2.5	11.1	20.7	24.1	33.0	6.8	1.7
0.5-1.0	1194	6.7	23.4	35.3	23.7	10.3	0.5	0.2
0-0.5	2355	15.1	49.0	27.3	6.0	2.3	0.2	0.0
–0.5-0	2264	18.4	30.7	20.6	12.5	12.9	4.6	0.2
< –0.5	522	1.0	10.7	20.7	20.9	30.7	12.5	3.6
All data	7091	12.3	31.9	25.3	14.0	12.4	3.4	0.7
Atmospheric stratification								
Stable	4305	10.5	35.1	28.3	14.0	9.9	1.6	0.6
Unstable	2786	15.1	27.0	20.6	14.1	16.3	6.1	0.8

–1.8 % of relative humidity, respectively. The mean deviation is 1.8 % of the mean relative humidity *rH* of the given data set (May to September). Approx. 50 % of the single data pairs deviate less than 1 % *rH* and approx. 80 % less than 2 % *rH* from each other. The frequency distribution is shown in Fig. 9.

It seems to be adequate to assume a total error of 2 % *rH* for the error propagation procedures in SVAT models, which is smaller than the error described in the standards.

3.5 Precipitation

For precipitation measurements, the deviation is determined by repeated measurements using standard equipment where height and intensity of precipitation are kept constant. The relative standard deviation is dependent on the measurement method as well as on the type of the instrument. For the type of instruments which are in common use this amounts to approx. 10 % (German standard VDI 3786 part 7, 1985) are considered normal.

At the Linden site two Hellmann gauges with tipping buckets were compared over a year. Only half-hourly periods with registered precipitation were compared. The two samplers deviate systematically: The zinc sampler collected less than the steel sampler (approx. 10 %). Two more standard Hellmann gauges with collecting cans were tested. Here, the zinc sampler collects more than the steel sampler: Event based sampling showed that approx. 0.1 mm was left on the steel gauge walls. These deviations are attributed to different surface properties and thus evaporation characteristics of the funnels.

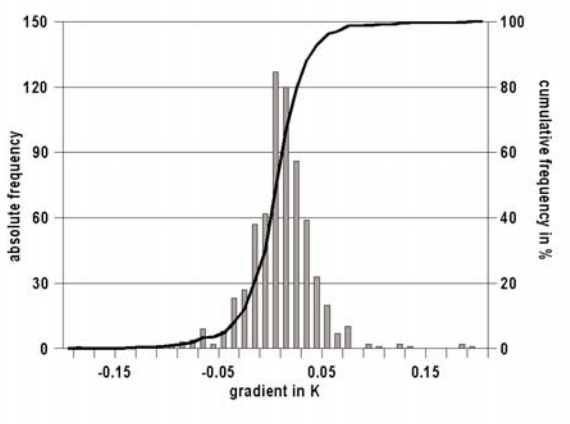

Fig. 8:
Absolute and cumulative frequency distribution of standard deviations of measured temperature gradients. FAL, 3 pairs of intercalibrated sensors, 3 locations, 8 m apart, z_1 = 2.5 m, z_2 = 1.0 m, 860 half hourly data sets.

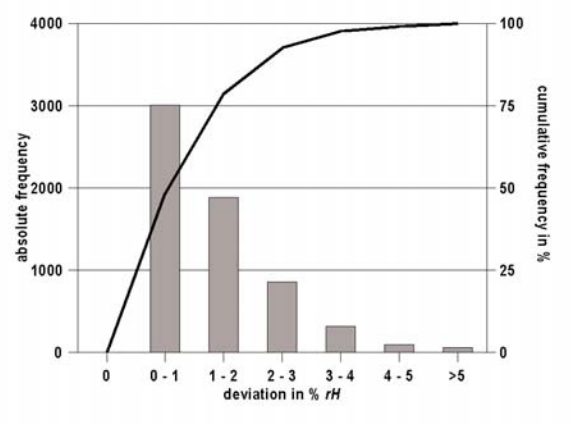

Fig. 9:
Frequency distribution of the deviations between an aspirated Frankenberger and a lithium chloride capacitive humidity sensors.

Comparison of the zinc Hellmann (funnel weathers) with 24 bulk samplers Rotenkamp B91 samplers (funnel properties do not change with time) which were exposed simultaneously at Linden over 6 years shows a very small effect of ageing (0.1 $mm \cdot a^{-1}$) which is negligible. However, the deviations between the "new" and the "old" Hellmann add up to a difference of approx. 5 to 10 %. This is only one of the potential systematic errors (cf Dämmgen et al., 2000, 2005).

Even for the 24 bulk samplers a mean standard deviation for monthly rain samples was approx. 4 %. This error is in the order of magnitude which is described in German standard DIN 58666 (1966).

After correction of systematic errors for half-hourly samples an error of 0.1 mm per period seems to be adequate. For parts of a year or a year the total error ranges from 5 to 10 %. Replicated sampling is strongly recommended. Correction for flow distortion seems to be mandatory whenever the samplers are not completely sheltered (see e.g. Richter, 1995).

If one considers that SVAT models should be calibrated and validated using water balance data, this error is totally unsatisfactory. Consequently, the use of one sampler only is insufficient.

4 Discussion and conclusions

"Good" data sets contain information about the errors involved. They provide tools to identify outlyers and artefacts and test the plausibility of the data recorded. Replicated sampling is the basis of error identification and should be performed throughout: none of the data lost can be reproduced; also, none of the instruments tested produced a signal which indicated misoperation or malfunction. Of course, the study of half-hourly data sets normally enables the experimenter to say that "something must have been wrong". It does, however, not provide a tool other than (linear or sophisticated) interpolation to repair the data set.

As costs have to be kept as low as possible, normal instrumentation comprises one set of instruments for each field site. On the other hand, data quality has to be assessed and error propagation procedures are to be performed. The data we compiled are thought to be applied to consistent and completed data sets to achieve at least the likely order of magnitude of the resulting error fit for error propagation.

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References

Dämmgen U, Erisman JW, Cape JN, Grünhage L, Fowler D (2005) Practical considerations for addressing uncertainties in monitoring bulk deposition. Environ Pollut 134:535-548

Dämmgen U, Grünhage L, Jäger H-J (1997) Description, assessment and meaning of vertical fluxes of matter within ecotopes: a systematic consideration. Environ Pollut 96:249-260

Dämmgen U, Grünhage L, Haenel H-D, Jäger H-J (1993) Climate and stress in ecotoxicology : a coherent system of definitions and terms. Angew Bot 67:157-162

Dämmgen U, Schaaf S, Frühauf C (2002) Accuracy and spatial representativity of heat flux measurements : a contribution to subproject BIATEX-2. In: Midgley PM, Reuther M (eds) Transport and chemical transformation in the troposphere : proceedings of EUROTRAC-2 Symposium 2002, Garmisch-Partenkirchen, Germany, 11-15 March 2002. Weikersheim : Margraf , on the enclosed CD-ROM

Dämmgen U, Scholz-Seidel C, Zimmerling R (2000) Die Qualität von Messungen der Bulk-Deposition anorganischer Spezies. Umweltplanung, Arbeits- und Umweltschutz, Sch R Hessische Landesanstalt Umwelt 274:130-177

German Standard DIN 58666 (1966) Meteorologische Geräte : Niederschlags-Auffanggerät, 200 cm^2 Auffangfläche. Berlin : Beuth

German standard VDI 3786 part 2 (2000) Meteorological measurements concerning questions of air pollution : wind. Berlin : Beuth

German standard VDI 3786 part 4 (1985) Meteorological measurements concerning questions of air pollution : air humidity. Berlin : Beuth

German standard VDI 3786 part 5 (1986) Meteorological measurements concerning questions of air pollution : Global radiation, direct solar radiation and net total radiation. Berlin : Beuth

German standard VDI 3786 part 7 (1985) Meteorological measurements concerning questions of air pollution : precipitation. Berlin : Beuth

German standard VDI 3786 part 13 (1993) Meteorological measurements : meteorological measuring station for agricultural purposes with computerized data handling. Berlin : Beuth

Grünhage L, Dämmgen U, Haenel H-D, Jäger H-J (1994) Response of a grassland ecosystem to air pollutants: III - the chemical climate : vertical flux densities of gaseous species in the atmosphere near the ground. Environ Pollut 85:43-49

Grünhage L, Haenel H-D (1997) PLATIN (PLant-ATmosphere INteraction) I : a model of plant-atmosphere interaction for estimating absorbed doses of gaseous air pollutants. Environ Pollut 98:37-50

Grünhage L, Haenel H-D (2001) Spatial variability of meteorological parameters, driving forces and fluxes. In: Midgley PM, Reuther M (eds) Transport and chemical transformation in the troposphere : proceedings of EUROTRAC-2 Symposium 2002, Garmisch-Partenkirchen, Germany, 11-15 March 2002. Weikersheim : Margraf, on the enclosed CD-ROM

Grünhage L, Haenel H-D, Jäger H-J (2000) The exchange of ozone between vegetation and atmosphere: micrometeorological measurement techniques and models. Environ Pollut 109:373-392

Grünhage L, Dämmgen U, Erisman JW, Lüttich M, Hanewald K, Jäger H-J, Freitag K, Baltrusch M, Liebl K (2002) Atmospheric nitrogen dynamics in Hesse, Germany : the challenge and its potential solution. Landbauforsch Völkenrode 52(4):219-228

Grünhage L, Schmitt J, Hertstein U, Janze S, Peter M, Jäger H-J (1996) Beschreibung der Versuchsfläche. Umweltplanung, Arbeits- und Umweltschutz, SchrR Hessische Landesanstalt Umwelt 220:49-71

Haenel H-D, Grünhage L (1999) Footprint analysis : a closed analytical solution based on height-dependent profiles of wind speed and eddy viscosity. Boundary-Layer Meteorol 93:395-409

Horst TW, Weil JC (1992) Footprint estimation for scalar flux measurements in the atmospheric surface layer. Boundary-Layer Meteorol 59:279-296

Horst TW (1999) The footprint for estimation of atmosphere-surface exchange fluxes by profile techniques. Boundary-Layer Meteorol 90:171-188

Jäger H-J, Grünhage L, Schmidt SW, Kammann C, Müller C, Hanewald K (2003) The University of Giessen Free-Air Carbon Dioxide Enrichment study : description of the experimental site and of a new enrichment system. J Appl Bot 77:117-127

Kormann R, Meixner FX (2001) An analytical footprint model for non-neutral stratification. Boundary-Layer Meteorol 99:207-224

Richter D (1995) Ergebnisse methodischer Untersuchungen zur Korrektur des systematischen Messfehlers des Hellmann-Niederschlagsmessers. Offenbach a M : Selbstverl d Deutschen Wetterdienstes, 93 p, Ber Dtsch Wetterdienstes 194

Schaaf S, Dämmgen U, Grünhage L (2005) The assessment of water vapour and carbon dioxide fluxes above arable crops – a comparison of methods. Meteorol Z, submitted

Schmid HP (1994) Source areas for scalars and scalar fluxes. Boundary-Layer Meteorol 67:293-318

Weigel H-J, Dämmgen U (2000) The Braunschweig Carbon Project : atmospheric flux monitoring and Free Air Carbon Dioxide Einrichment (FACE). J Appl Bot 74:55-60