

On the efficiency and correction of vertically oriented blunt bioaerosol samplers in moving air

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Abstract The aspiration efficiency of vertical and wind-oriented Air-O-Cell samplers was investigated in a field study using the pollen of hazel, sweet chestnut and birch. Collected pollen numbers were compared to measurements of a Hirst-type Burkard spore trap. The discrepancy between pollen counts is substantial in the case of vertical orientation. The results indicate a strong influence of wind velocity and inlet orientation relative to the freestream on the aspiration efficiency. Various studies reported on inertial effects on aerosol motion as function of wind velocity. The measurements were compared to a physically based model for the limited case of vertical blunt samplers. Additionally, a simple linear model based on pollen counts and wind velocity was developed. Both correction models notably reduce the error of vertically oriented samplers, whereas only the physically based model can be used on independent datasets. The study also addressed the precision error of the instruments used, which was substantial for both sampler types.

Keywords Burkard sampler · Air-O-Cell sampler · Orifice orientation · Birch pollen · Field measurement

Introduction

Experimental investigation of local aerosol dispersion requires both spatially and temporally detailed information on their concentrations. Spatial resolution is often limited by the availability of instruments. Therefore, different instrument types may be used in order to increase the instrumental set-up, i.e., spatial information. The comparability of different aerosol sensors, however, presumes a knowledge of their aspiration characteristics. The present study was motivated by a field experiment (Michel et al. 2010) in which different bioaerosol samplers were used to sample birch pollen (22 μm diameter). The measurements indicate a substantial discrepancy between wind-oriented Hirst-type (Hirst 1952) Burkard samplers and vertically oriented Air-O-Cell samplers. The latter were facing upwards to make the measurements independent of wind direction. In the present study, field intercomparison of Burkard and Air-O-Cell samplers was carried out during the birch pollen season in 2010. The Air-O-Cells were oriented vertically as well as horizontally. The effect of orifice orientation on the aspiration efficiency (i.e., the ratio of sampled aerosols to the aerosol number in the considered volume of air upstream of the orifice) is well-known (Ogden et al. 1974). Aspiration is related to inertial effects on particle motion. As the angle between the orifice and the freestream increases, the behavior of the flow approaching a sampler is progressively complicated, and the aspiration efficiency decreases dramatically (Lundgren et al. 1978; Vincent et al. 1986). Thus, in the case of vertically oriented blunt samplers, which represents most pollen samplers used in the field (Levetin 2004), a correction of the measured data is indispensable. It would be of great benefit to bioaerosol-related research (e.g., the advancing field of aeroallergenic studies), if corrections of measured data were performed at experimental as well as

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operational stations. The impaction efficiency of Air-O-Cell and Burkard samplers (i.e., the ratio of sampled aerosols to the number of aspirated aerosols) was investigated under laboratory conditions by Aizenberg et al. (2000). Their results indicate a good agreement of the Air-O-Cell with the Burkard sampler for small fungal and bacterial aerosols ($< 3.5 \mu\text{m}$). The aspiration efficiency of the Burkard sampler was determined under laboratory conditions with respect to wind velocity and pollen size by Hirst (1952) and Ogden et al. (1974). For Ambrosia pollen, which have a similar size as birch pollen ($20 \mu\text{m}$), Ogden et al. (1974) found an efficiency declining to 60% for wind velocities $< 5 \text{ms}^{-1}$. A physically based semi-empirical model accounting for the effects of vertical oriented sampler inlets, wind velocity and bluntness of the sampler body on aerosol motion has been developed by Tsai and Vincent (1993). In the present work, this aspiration model was verified with the measured data of the sampler intercomparison. The deviation of vertical Air-O-Cells from Burkard measurements could be reduced notably. Additionally, an alternative linear correction model was constructed on the basis of pollen counts and wind velocity. The linear correction yields a better agreement of Air-O-Cells with the Burkard sampler, yet it cannot be transferred to independent datasets.

Apart from aspiration efficiency, uncertainties are also induced by the manual sample analysis, which is still the standard at most operational pollen observation sites. Large errors may occur when aerosol deposition on the impaction area is inhomogeneous. In the present study, this applies only to the Burkard sampler, since the Air-O-Cell counting covers the entire impaction area. Laboratory and field studies (Comtois et al. 1999; Aizenberg et al. 2000; Gottardini et al. 2009) on pollen density distribution on the slide of volumetric pollen samplers showed that the distribution is mostly inhomogeneous and dependent on pollen size.

Materials and Methods

Pollen sampling methods

The instrument set-up included two different types of bio-aerosol samplers, which both use the impaction principle, where aerosols impinge on a sampling substrate as an effect of greater inertia than that of air, accelerated by aspiration. The Air-O-Cell (A) sampler (Zefon International, <http://www.zefon.com>; Levetin 2004) is a disposable cylindrical cassette, which includes a sampling substrate-coated glass slide. Its orifice tapers to a slit of $14.4 \text{mm} \times 1 \text{mm}$. The instrument can be mounted wind-oriented (horizontally) when the wind direction is persistent, or facing upwards (vertically), making the measurements independent of wind direction. In the present study both orientations were used.

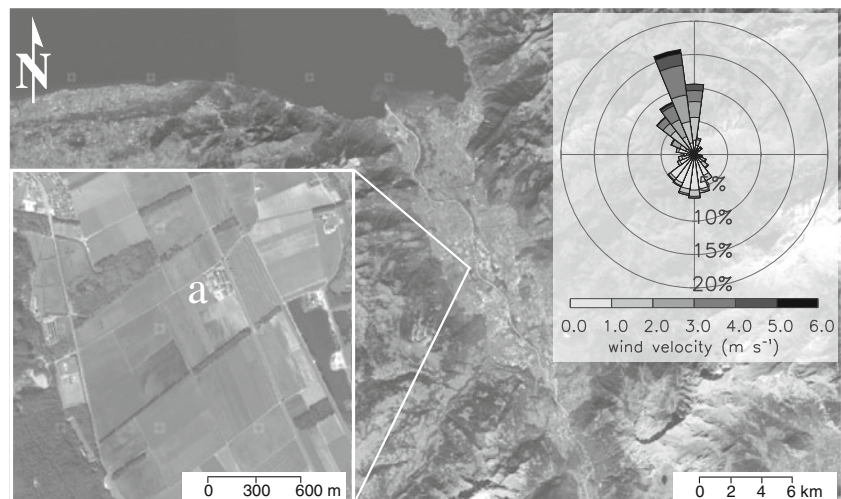
The Air-O-Cell cassette needs to be connected to a pump, which is capable of producing an sampling rate of 15lmin^{-1} . The pump provided by Zefon is not suitable for experimental outdoor use and very costly if a larger array of A samplers is to be equipped. Therefore, an alternative self-constructed aspiration system consisting of parallel membrane pumps was attached to the cassettes conferring a cylindrical shape on the total A sampler (see Fig. 2). The system provides a sampling rate of 18.5lmin^{-1} , which exceeds the factory-recommended minimal sampling rate. A larger sampling rate increases the range of sampled particles towards lighter particles. The temporal resolution is determined by the cassette exposure. The sampling rate was monitored in situ using a thermal gasflowmeter (red-y smart, Vögtlin Instruments, Aesch, Switzerland). The exposure time was 45 min, then the cassettes were replaced. The collected pollen numbers were extrapolated to obtain a 1-h resolution. The pollen counting procedure covered the entire impaction area.

The Burkard (B) sampler (Burkard Manufacturing, Rickmansworth, UK) is a wind-oriented instrument with a $2 \text{mm} \times 14 \text{mm}$ slit orifice (Mandrioli et al. 1998). The sampling rate is 10lmin^{-1} . Particles are collected on an adhesive sampling tape mounted on a rotating cylinder, which provides a continuous 7-day information on pollen concentration. The temporal resolution depends on the analysis method. In the present study, a 1-h resolution was obtained. Four or five longitudinal counting sweeps were performed across the impaction area, which yields a coverage of 20.5 and 25.7%, respectively. The total pollen number was extrapolated to the entire impaction area. The body shape (i.e., bluntness) is similar to that of the human head, since the B sampler was designed to measure inhalable aerosols rather than their atmospheric concentration. The B sampler is used commonly in European bioaerosol monitoring networks. In the present study, therefore, their measurements are taken as a reference.

Sampler intercomparison experiment

The sampler intercomparison was conducted in Illarsaz, Switzerland during the emission period of birch (*Betula*) pollen from 5–23 April 2010. The study site (Fig. 1) was located in a valley where birch is common. The region is dominated by a plains-mountain wind system with persistent wind conditions (mean wind direction 350° during daytime and southerly wind during the night). Knowledge of the predominant daytime wind direction was used to align the instrument set-up normal to the mean wind direction. A small spatial instrument separation ($< 10 \text{m}$) was chosen to minimize sampling discrepancies due to inhomogeneities of the atmospheric pollen distribution (Fig. 2). In the case of

Fig. 1 Satellite images of the experiment locations in Illarsaz, Switzerland (top left Lake of Geneva). *Inset, lower left* Location of intercomparison experiment 2010 (a). *Inset, top right* The frequency of wind direction and velocity measured at a. Federal Office of Topography swisstopo (<http://www.swisstopo.admin.ch/internet/swisstopo/en/home.html>)



low concentrations, however, atmospheric inhomogeneities may induce large relative sampling errors of 1-h averages. The measuring height was 2 m above the ground.

The intercomparison set-up consisted of two B samplers and four A samplers; two A samplers were oriented horizontally (A_h , where the subscript refers to orientation), facing the mean wind. Two A samplers were oriented vertically (A_v), facing upwards. This set-up was chosen in order to assess the difference between the A and B sampler when both are mounted such that the orifice faces the mean wind direction, as well as the impact of vertical orientation of the A sampler. Simultaneously, a USA-1 ultrasonic anemometer (METEK, Elmshor, Germany, 10 Hz) was mounted at 2 m above the ground and 21 m upwind of the bioaerosol samplers to monitor the wind velocity. The B samplers as well as the sonic anemometer were operated during the entire campaign period. The A samplers were operated only during periods of favourable wind conditions (i.e., northerly wind direction).

Additional data were available for different pollen species [hazel (*Corylus*), 28 μm average diameter and sweet

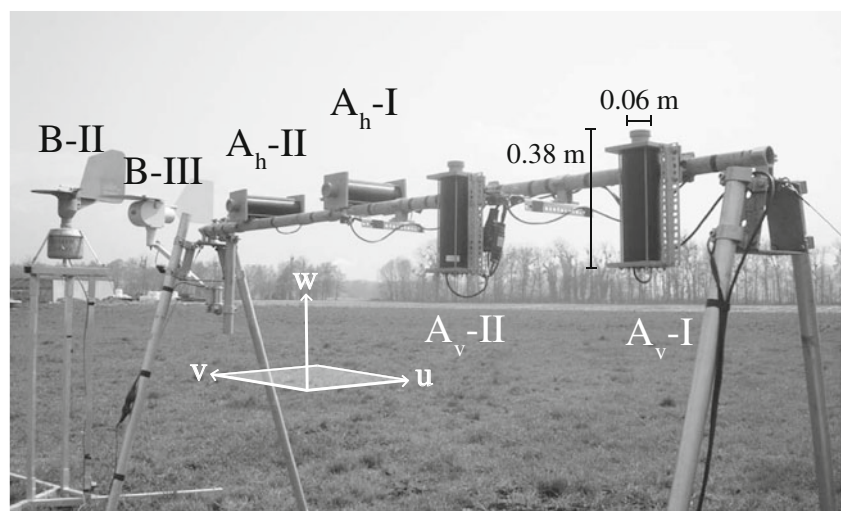
chestnut (*Castanea*), 14 μm average diameter, Bucher et al. (2004)]. These shorter intercomparisons were conducted in 2009 using a similar experimental arrangement as in Fig. 2, but at operational MeteoSwiss pollen monitoring sites.

Post-processing

The pollen concentration of B samples was calculated according to the recommendations of Mandrioli et al. (1998). In the case of A samplers, the pollen concentration was calculated as the ratio of the total pollen count and the aspirated volume of air. Since the exposure time was only 45 min, the concentration was extrapolated to 1 h. This may have led to a certain error when compared to B measurements, because pollen transport occurs as intermittent gusts rather than a steady pollen flux.

With respect to the azimuth of the horizontal A samplers (350°), only wind directions related to the mean wind direction $\pm 50^\circ$ were accepted for analysis.

Fig. 2 Set-up of instruments in the sampler intercomparison in Illarsaz 2010. Sampler B-I was mounted at the far right side of this figure. The coordinate system denotes the orientation of the wind components relative to the instrument orientation. Measurements from the Burkard Scientific sampler (B-III) were not used in the present study. The dimensions of the A sampler including the pump housing are specified for A_v -I



Overview on the sampler agreement

Prior to the comparison of different sampler types, the precision of each sampler type B , A_v and A_h was addressed separately on the basis of sweet chestnut and birch pollen measurements by analyzing pairs of identical sampler types.

The dataset of hazel pollen was not taken into account because the sample size was too small. The measurements indicate a good correlation of all sampler types ($R^2 \geq 0.61$, Table 1). The root mean square error (rmse) is used to quantify the precision of the instruments. The relative rmse is calculated as rmse normalized by $\langle \bar{c} \rangle$, where $\langle \bar{c} \rangle$ is the spatial and temporal average of the two measurements (e.g., $A_v - I/II$). The relative rmse of the A and B samplers is rather large (from 26% to 57%). The large error among the vertically oriented A samplers may have resulted from strong statistical effects of atmospheric inhomogeneities in the case of low $\langle \bar{c} \rangle$ measurements. In contrast, horizontal A samplers agree comparably well, since the observed $\langle \bar{c} \rangle$ is considerably larger. The large uncertainty among the B samplers arises from the counting procedure rather than from the aspiration efficiency. The agreement among identical sampler types is summarized in Table 1.

A re-analysis of three B slides was performed in order to quantify the influence of the number of sweeps on the calculated pollen concentration. The slides have been re-counted on the basis of 24-h -slides with 4 and 30 longitudinal sweeps of 0.36 mm width, which yields a coverage of 10% and 77%, respectively, of the impaction area (48×14 mm). Figure 3 illustrates that the position of the sweeps has a strong influence on the extrapolated total, if the distribution is not homogeneous (e.g., bipolar). Cariñanos et al. (2000) investigated different pollen counting methods of slides using a Hirst-type sampler. They found an overestimation of extrapolated pollen numbers when the sweeps are positioned in the middle of the slide, where most pollen are deposited. The present counting method considered depositions near the edge of the impaction area as well in the center. The variation in the numbers of sweeps yielded a relative error of 16%, when only 10% of the deposition area

Table 1 Precision of different sampler types. The relative root mean square error (rmse) is calculated as rmse normalized by $\langle \bar{c} \rangle$, where rmse denotes the root mean square difference of two samplers (I and II) with the same orientation and $\langle \bar{c} \rangle$ is the spatial and temporal average of the two samplers. n Sample size

Pollen species sampler	Sweet chestnut Av-I/II	Birch Av-I/II	Birch Ah-I/II	Birch B-I/II
R^2	0.61	0.89	0.96	0.90
relative rmse [%]	37	57	26	38
$\langle \bar{c} \rangle$ [pollen m^{-3}]	19.0	25.3	684.7	848.9
n	24	47	47	47

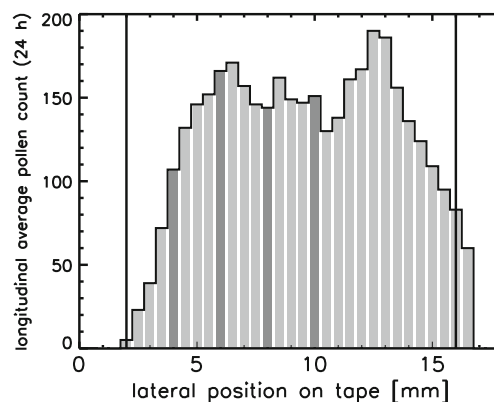


Fig. 3 Lateral pollen deposition on the Burkard sampling slide obtained from 24-h averages of longitudinal pollen counts. Gray area Absolute pollen counts (y-axis) and analyzed area (x-axis) when 30 sweeps were performed, dark gray bars four sweeps only performed, black vertical lines outer limits of impaction area, which corresponds to the inner inlet orifice (2×14 mm)

was analysed instead of 77%. Comtois et al. (1999) found a larger relative error (almost 30%) in the case of four sweeps (slide coverage of 13.3%), when 100% of the entire slide was analyzed.

Quantification of the error induced by vertical orientation

For the following sampler intercomparison, spatial averages of aspirated pollen concentrations, c , i.e., for example $\langle c_{Av} \rangle$, are analyzed, denoted as c_{Av} , c_{Ah} and c_B , respectively, where the subscripts refer to sampler type and orientation. The bias denotes the mean deviation of a data series from the reference. The relative bias is calculated as bias normalized by \bar{c} of the reference instrument. The relative rmse is calculated as rmse normalized by \bar{c} of the reference instrument.

Figure 4 illustrates that the aspiration efficiency is decreased when the sampler orifice is facing upwards. Hence, the vertically oriented samplers underestimated the pollen concentration dramatically in comparison to the B sampler. In the case of sweet chestnut pollen, the relative bias was -70% . The birch pollen measurements underestimated the concentration with an error of almost three orders of magnitude, with a relative bias of -104% . The better agreement of the sweet chestnut measurements is a result of their lower inertia compared to the larger birch pollen. The majority of the vertically measured concentrations did not exceed 60 pollen m^{-3} , while c_B observations range up to 5×10^3 pollen m^{-3} .

The aspiration efficiency of the horizontal A samplers facing the freestream, in contrast, is considerably better. The c_{Ah} data agree well with the B samplers ($R^2=0.76$). However, the A_h samplers also slightly underestimate the pollen concentration, with a relative bias of -20% . The impaction efficiency of the A cassette already tends towards 100% with aerosols of an aerodynamic diameter up to $5 \mu m$

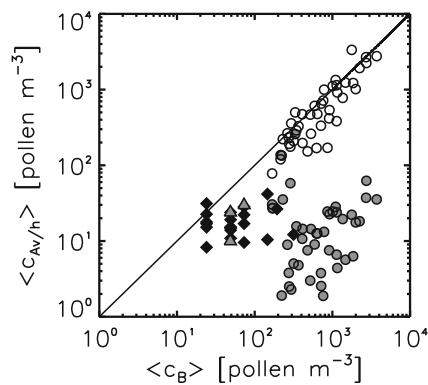


Fig. 4 Agreement of 1-h pollen concentrations measured with B and A samplers; *triangles* hazel, *squares* sweet chestnut, *circles* birch pollen. *Filled symbols* A_v data, *open symbols* A_h data. In the case of the birch pollen dataset, only cases where the wind direction was $\pm 50^\circ$ compared to the azimuth of the A_h samplers are shown. Note that the plot is double-logarithmic

(Aizenberg et al. 2000), i.e., much smaller and lighter than birch pollen (22 μm diameter; Birks 1968). Hence, the error of the A_h sampler is due mainly to its blunt design, diverting the approaching freestream. The relative bias between birch c_{Av} and c_{Ah} amounts to -105% . This denotes a very large error between identical samplers, which is induced by their orientation. The relative errors of the A_v sampler are summarized in Table 3.

Aspiration characteristics of blunt samplers at different orientations

Experimental and theoretical work on the determination of the aspiration efficiency of aerosol samplers related mostly to thin-walled, tubular inlets facing the freestream, e.g., Badzioch (1959) and Belyaev and Levin (1974). This idealization was a starting point to understanding the basic principles that determine aspiration efficiency. In practice, however, the flow pattern upstream of a sampler orifice is much more complex. It is affected by various parameters, such as the orientation, θ , of the orifice relative to the freestream, the aspiration velocity and the characteristic bluntness of the sampler body. Vincent et al. (1986) have investigated the physics of thin-walled samplers with respect to their orientation relative to the freestream. Based on his work, Tsai and Vincent (1993) developed a model for the range of blunt samplers, which was assessed in the present for the single case of vertical orientation.

In theory, the aspiration efficiency of a sampler is defined by:

$$E_t = c/c_0, \quad (1)$$

where c is the particle concentration entering the plane of the sampler inlet, and c_0 is the upstream concentration, given that the air and particle velocity distributions are

uniform. Taking into consideration the influence of inertial effects on the aspiration efficiency due to divergence and convergence of the flow as it approaches the sampler inlet, Eq. 1 can be extended to:

$$E = \frac{c}{c_0} = 1 + \beta(R - 1), \quad (2)$$

where β is the impaction efficiency, defined as the ratio between the number of particles impacting onto the virtual plane between the limiting trajectories, and the number of particles impacting onto the plane of the sampling orifice. A robust empirical expression for β (Vincent 2007) is:

$$\beta = 1 - \frac{1}{1 + GSt}, \quad (3)$$

where St is the particle Stokes number and G is an empirical coefficient, which was investigated by Belyaev and Levin (1974) and Paik and Vincent (2002). R is defined as:

$$R = \frac{U}{U_s}, \quad (4)$$

where U is the freestream velocity and U_s is the sampling velocity through the sampling plane. The sampling velocity of the A sampler is $U_s = 1.84 \text{ m s}^{-1}$. In the case of idealized thin-walled samplers, $R=1$ denotes isokinetic sampling, where $E_t=1$. If sampling is sub-isokinetic ($R>1$) or super-isokinetic ($R<1$), the trajectories of the air flow are divergent or convergent, respectively, and particles are either gained or lost at the sampler inlet due to inertial effects on the particle motion. With respect to orientations up to $\theta=90^\circ$, Eq. 2 can be expressed by an impaction model, which in similar form was used by Belyaev and Levin (1974); Durham and Lundgren (1980); Vincent et al. (1986); Wiener et al. (1988); Lipatov et al. (1988); Vincent (1989); Grinshpun and Lipatov (1990); Hangal and Willeke (1990a, b); Grinshpun et al. (1994) and Vincent (2007):

$$E_\theta = \frac{c}{c_0} = 1 + \beta_\theta(R \cos \theta - 1) \quad (5)$$

The aspiration performance of a blunt sampler facing upwards in calm air, i.e., for super-isokinetic sampling, has been investigated by Dunnett et al. (2006). The particle Stokes number St accounts for turbulent particle motion, i.e., the inertially dominated behavior of particles in a distorted flow and is defined as:

$$St = \frac{\tau U}{\delta}, \quad (6)$$

where δ is the sampling orifice width, and τ is the response time of the particle to perturbation. It can be expressed as:

$$\tau = \frac{\gamma^* d_{ae}^2}{18\mu}, \quad (7)$$

where μ is the dynamic molecular viscosity of air, and d_{ac} is the aerodynamic particle diameter. d_{ac} characterizes a sphere with the density equivalent to water $\gamma^*=1 \text{ g cm}^{-3}$ and, therefore, has the same settling velocity as the particle in question. For laminar flow d_{ac} is defined as:

$$d_{ae} = d \left(\frac{\gamma}{\gamma^*} \right)^{1/2}, \quad (8)$$

where d is the particle diameter.

Thus, the Stokes number denotes the ratio of the stopping distance τU_0 of the particle to the width of the sampler orifice, when the particle motion is turbulent, i.e., within distorted flow. Small values of St indicate that the particles tend to follow the fluid trajectories, while large values indicate a separation of particle motion from the fluid motion.

Based on experimental studies on the human head (Ogden and Birkett 1977; Armbruster and Breuer 1982) and cylindrical thin-walled samplers (Vincent et al. 1986), an aspiration model for the limited case of blunt samplers with orientation $\theta = 90^\circ$ was developed (Tsai and Vincent 1993). It is expressed as:

$$E_{90} = \frac{1}{1 + 4G_{90}r^{g_1} StR^{1/2}}, \quad (9)$$

where G_{90} and g_1 are both empirical coefficients. Tsai and Vincent (1993) obtained an agreement of the corrected data of $R^2=0.61$ for $G_{90}=2.21$ and $g_1=-0.5$, where G_{90} is a scale of the sampler bluntness and g_1 is a modification of the inlet dimension ratio $r=\delta/D$, where D is the characteristic sampler width. It is important to understand that the area projected upstream by the sampler body, i.e., its bluntness, increases with θ (Lundgren et al. 1978). Assuming $r=1$, the term $G_{90}r^{g_1}$ approaches the bluntness of a thin-walled sampler, which was empirically determined to be $G_{90}=2.1$ for θ up to 90° (Vincent et al. 1986).

An alternative linear correction for vertical aspiration using wind velocity

Aspiration efficiency is dependent strongly on the sampler design, i.e., affected by the characteristic bluntness of the sampler body and the inlet design, described with r . It is unknown to what extent the findings of human head studies (Ogden and Birkett 1977; Armbruster and Breuer 1982; Vincent et al. 1986) apply to the bulky body of the A sampler in the present work. Therefore, an alternative approach to the correction of vertical aspiration is presented, which applies only to the exact experiment sites of the present study and that of Michel et al. (2010).

Based on the knowledge of inertial effects on suspended particle motion, the relation between wind velocity and the discrepancy between A_v and A_h samplers was determined using the data collected during sampler intercomparison in order to

obtain a relative correction of A_v against A_h . The correlation of the corrected A_v with the B data was then determined.

Since the A_h sampler azimuth is fixed, i.e., not automatically wind-oriented, the effect of yaw orientations needed to be minimized. Therefore, only the wind component u facing the A_h sampler orifices with a threshold of $\pm 50^\circ$ were accepted for analysis. Hence, R is expressed as $R=\bar{u}/U_s$. Figure 5 shows that the slope of c_{Av} deviations from c_{Ah} is steeper, when $R>1$, than for cases where $R<1$. Therefore, the linear regression was calculated separately for cases where $R\leq 1$ and $R>1$. Consequently, the correction procedure incorporates sub-models separated according to the longitudinal wind velocity. The correlation of A_v with A_h data provided two models, which use different sets of coefficients according to values of u (Eqs. 10, 11):

$$c_{lin}^* = \alpha_1 c_{Av} + \alpha_2 \bar{u}, \quad \text{if } R \leq 1 \text{ and } c_{Av} > 0 \quad (10)$$

$$c_{lin}^* = \alpha_3 c_{Av} + \alpha_4 \bar{u}, \quad \text{if } R > 1 \text{ and } c_{Av} > 0, \quad (11)$$

where c_{lin}^* denotes the corrected pollen concentration.

In a second step, the c_{lin}^* data are fitted against the B data to decrease the offset indicated in Fig. 4 between B and A_h measurements. The resulting linear correction model is defined as:

$$c_{lin}^{**} = \beta_1 c_{lin}^*, \quad \text{if } c_{lin}^* > 0 \quad (12)$$

where c_{lin}^{**} refers to the concentration of the vertically oriented A samplers after the 'double correction'. The goodness-of-fit and coefficients of linear models c_{lin}^* and c_{lin}^{**} are shown in Table 2.

Results

Performance of the physically based aspiration model

The aspiration model for upwards-facing blunt samplers (Eq. 9) was tested against the measured aspiration efficiency

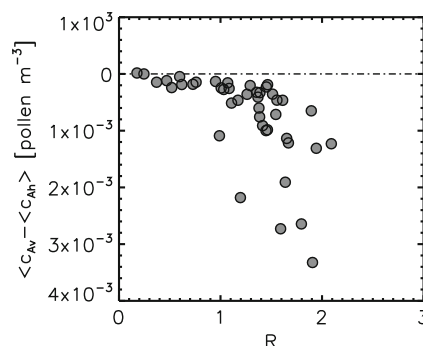


Fig. 5 The difference $c_{Av}-c_{Ah}$ as a function of $R=\bar{u}/U_s$, where \bar{u} is the longitudinal wind component, and U_s is the sampling velocity of the Air-O-Cell sampler (1.84 ms^{-1})

Table 2 Goodness-of-fit and coefficients of statistical models. c_{lin}^* denotes the linear correction of A_v data using Eqs. 10 or 11 according to the longitudinal wind velocity component \bar{u} , c_{lin}^{**} denotes the linear correction of A_v data using Eq. 12

Correction	Validity range	Predictors	R^2	P-value
c_{lin}^*	$R \leq 1$	$c_{Av}; \bar{u}$	0.62	0.01
c_{lin}^*	$R > 1$	$c_{Av}; \bar{u}$	0.78	$1.04 \cdot 10^{-10}$
c_{lin}^{**}	Entire data range	c_{lin}^*	0.85	$2.2 \cdot 10^{-16}$
Coefficients				
c_{lin}^*	$R \leq 1$	0.91 (α_1)	225.93 (α_2)	
c_{lin}^*	$R > 1$	36.09 (α_3)	176.02 (α_4)	
c_{lin}^{**}	Entire data range	1.17 (β_1)		

of A_v samplers, assuming a birch pollen diameter $d=22 \mu\text{m}$ (Birks 1968) and a density $\gamma=800 \text{ kg m}^{-3}$. The measured aspiration efficiency of the vertical samplers was determined with $E_{Av}=c_{Av}/c_B$. Note that the aspiration of the B sampler underlies the same inertial effects discussed above. Its bulky body presents a considerable obstacle to the freestream, which distorts the freestream as it approaches the sampler. Since the B sampler was designed to rather register inhalable aerosols, its readings do not exactly represent the atmospheric concentration. The ‘true’ aspiration efficiency of the B sampler was determined by Ogden et al. (1974) using Ambrosia pollen ($20 \mu\text{m}$). A mathematical equation for the empirical data was provided by Frenz (1999). Figure 6 shows that the B sampler aspiration declines to 60% at $U=5 \text{ ms}^{-1}$. With increasing wind velocity, the aspiration efficiency exceeds 100%. Hence, measurements aiming at the atmospheric aerosol concentration need to be corrected with respect to wind velocity. The physically based aspiration model, however, was derived also from studies on inhalability by the human head. Therefore, comparison of the model to the uncorrected B sampler seems reasonable.

Figure 7 shows that the physically based model dramatically overestimates the aspiration efficiency of the A_v

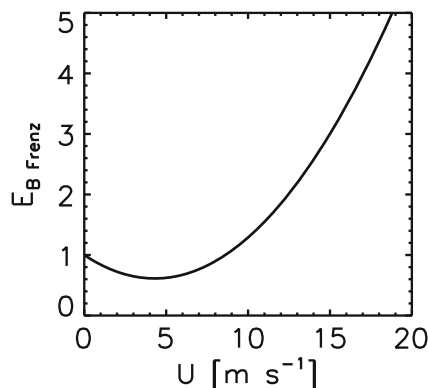


Fig. 6 Aspiration efficiency of the Burkard sampler as a function of the wind velocity U , using the mathematical equation provided by Frenz (1999) based on the empirical data of Ogden et al. (1974)

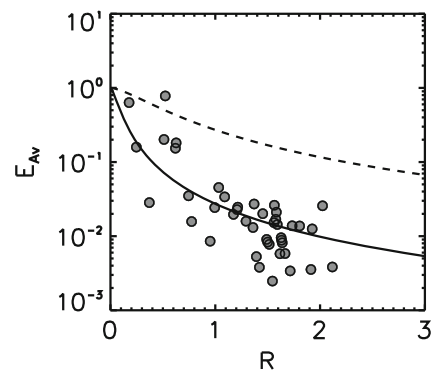


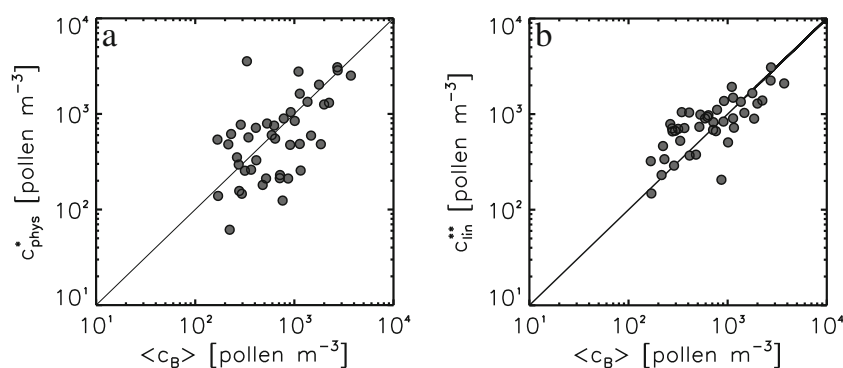
Fig. 7 Measured aspiration efficiency $E_{Av}=c_{Av}/c_B$ plotted as a function of $R=U/U_s$, where U is the freestream velocity and U_s is the sampling velocity of the Air-O-Cell sampler (1.84 ms^{-1}). Solid curve Modeled aspiration efficiency E_{90} using $G_{90}=2.21$ and $g_1=-1$, dashed curve modeled (Eq. 9) using $G_{90}=29.35$ and $g_1=-0.5$. Note that the y-axis is logarithmic

sampler, when the empirical value $G_1=2.21$ determined from human head studies (Tsai and Vincent 1993), is used. The best results (i.e., the lowest bias) for the A_v data yields $G_{90}=29.35$ with $g_1=-0.5$. Thus the parameter G_{90} needs substantial modification for the vertical A sampler, since the greater bluntness of the sampler body must be taken into account. It seems that the exact value of G_{90} is a strong function of the very sampler design. To what extent this value can be considered characteristic for an Air-O-Cell sampler depends on the dimension of the pump housing. Thus it would be helpful to determine the dependence of G_{90} on different sampler designs. The model was used with $G_{90}=29.35$ to correct the vertically measured data through:

$$c_{phys}^* = \frac{1}{E_{90}} c_{Av}, \tag{13}$$

where c_{phys}^* denotes the corrected A_v pollen concentration. Note that the data are corrected only when the deviation from B samplers is larger than the rmse of the B samplers. The correlation of the corrected data ($R^2=0.39$) is considerably less than that of Tsai and Vincent (1993) for their aerosols of aerodynamic diameters up to $60 \mu\text{m}$. The model generally underestimates the measurements when $R \leq 1$, and generally overestimates when $R > 1$. The relative bias and relative rmse between c_{phys}^* and c_B is 0% and 89%, respectively. Figure 8a shows that the corrected data as a function of c_B are widely scattered. A significant correlation can be found only due to a satisfying agreement for pollen concentrations $c > 1 \times 10^3 \text{ pollen m}^{-3}$. Since no pollen counts are considered in Eq. 9, the physically based correction can not take into account errors that are induced by effects other than the aspiration efficiency, e.g., the error due to the extrapolation of A sampler data, as discussed earlier. The errors of the uncorrected and corrected data are summarized in Table 3.

Fig. 8 **a** Corrected 1-h A_v data (c_{phys}^*) using the physically based model, as function of c_B . **b** Corrected 1-hour A_v data (c_{lin}^{**}) using the linear model, as function of c_B . Note that the plots are double-logarithmic



Performance of the linear correction model

The performance of the linear correction was tested against B sampler measurements. The linear model was used to correct the vertically measured data. Note that the data are corrected only when the deviation from B samplers is larger than the rmse of the B samplers. The correlation of the corrected data is $R^2=0.63$ and the relative rmse is 57%. Although the error is still relatively large, it is not substantially larger than the precision error of the B sampler (Table 1). The relative bias of 3% indicates a slight overestimation of the corrected c_{lin}^{**} . Figure 8b shows that the scatter of the corrected data c_{lin}^{**} as function of c_B is considerably less than in the case of the physical model. The linear correction takes into account the measured pollen concentration. Therefore, errors resulting from, e.g., the extrapolation of A sampler data, are taken into account to a certain extent. The errors of the uncorrected and corrected data are summarized in Table 3.

Table 3 Summary of relative bias (mean deviation normalized by the corresponding mean pollen concentration $\langle \bar{c} \rangle$ shown in Table 1) and relative rmse (normalized by the corresponding mean pollen concentration $\langle \bar{c} \rangle$ shown in Table 1) between uncorrected and corrected A_v and B samplers (reference) using the physically based and the linear model, respectively. c_{Av} denotes uncorrected measurements of the vertically oriented A_v sampler, c_{Ah} denotes measurements of the horizontally oriented A_h sampler, c_B denotes measurements of the B sampler, c_{lin}^{**} denotes the corrected c_{Av} data using the linear model (Eq. 12) and c_{phys}^* denotes the corrected c_{Av} data using the physically based model (Eq. 9). The values of the relative bias and relative rmse are given in percent

Data	c_{Ah} (Reference)			c_B (Reference)		
	Relative bias	Relative rmse	R^2	Relative bias	Relative rmse	R^2
c_{Av}	-105	154	0.00	-104	140	0.00
c_{Ah}	-	-	-	-20	50	0.76
c_{lin}^*	9	74	0.60	-	-	-
c_{lin}^{**}	-	-	-	3	57	0.63
c_{phys}^*	-	-	-	0	89	0.39

Conclusions

The present work quantified in a field experiment the uncertainty of vertically oriented blunt aerosol sampling systems using Air-O-Cell cassettes. The investigation focussed on the decrease of vertical pollen aspiration (hazel, sweet chestnut and birch) due to inertial effects on aerosol motion in moving air. The aspiration efficiency of the vertical samplers was determined with wind-oriented reference samplers (Hirst-type Burkard sampler, horizontal Air-O-Cell sampler). The decrease of aspiration efficiency of the vertically oriented sampler resulted in a substantial underestimation of the pollen count relative to horizontal measurements (-104% relative bias). This underlines the importance of applying a correction when the sampler inlet is facing upwards, as is quite common in, e.g., aeroallergenic research. Wind-oriented mounting of the same sampler type yields an considerably smaller underestimation relative to horizontal measurements (-20% relative bias). A physically based semi-empirical correction model was verified with birch pollen measurements for the purpose of the vertically oriented Air-O-Cell sampler. Additionally, a linear model was developed on the basis of pollen counts and wind velocity measurements. Both models were capable of notably reducing the error induced by vertical sampling. In comparison to the physical model, the linear correction yielded a better agreement to the reference. The linear model, however, is valid only under the very conditions of the experimental site and for the specific sampler design. The physically based model, in contrast, can be transferred to each upwards-facing blunt sampler type. It should be noted, however, that the characteristic bluntness of a sampler might make a modification of the semi-empirical model necessary in order to provide a robust correction.

The precision error of the wind-oriented Air-O-Cell sampler is rather large (26% of the mean concentration), yet is smaller than the precision error found for the Burkard sampler (38%). The Air-O-Cell cassette itself, therefore, can be considered a good low-priced alternative to, e.g., the widely used Burkard sampler. Attention should focus on the pump housing that is attached to the sampling cassette, however, since it may strongly affect the aspiration efficiency.

The results of the sampler intercomparison clearly point out that aspiration of aerosols (i.e., heavy aerosols such as pollen) should always be wind-oriented. In the case of blunt samplers and non-isokinetic sampling, the sampling error is a function of wind velocity, also in the case of a wind-oriented inlet. Thus under field conditions, a physically based correction of pollen counts is indispensable.

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