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Vertical divergence of fogwater fluxes above a spruce forest

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Abstract

Two almost identical eddy covariance measurement setups were used to measure the fogwater fluxes to a forest ecosystem in the "Fichtelgebirge" mountains (Waldstein research site, 786 m a.s.l.) in Germany. During the first experiment, an intercomparison was carried out with both setups running simultaneously at the same measuring height on a meteorological tower, 12.5 m above the forest canopy. The results confirmed a close agreement of the turbulent fluxes between the two setups, and allowed to intercalibrate liquid water content (LWC) and gravitational fluxes. During the second experiment, the setups were mounted at a height of 12.5 and 3 m above the canopy, respectively. For the 22 fog events, a persistent negative flux divergence was observed with a greater downward flux at the upper level. To extrapolate the turbulent liquid water fluxes measured at height z to the canopy of height h_c, a conversion factor $1/[1+0.116(z-h_c)]$ was determined. For the fluxes of nonvolatile ions, no such correction is necessary since the net evaporation of the fog droplets appears to be the primary cause of the vertical flux divergence. Although the net evaporation reduces the liquid water flux reaching the canopy, it is not expected to change the absolute amount of ions dissolved in fogwater.

Keywords: Fog; Eddy covariance method; Flux measurements; Flux divergence; Deposition; Droplet size

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1. Introduction

Many forest ecosystems in the elevated regions receive a significant fraction of their water input by the interception of the fogwater. In the 1980s, most studies dealing with the

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estimation of the amount of deposited fog and cloud water were based on flux-gradient assumptions, deposition of velocity calculations, or other indirect methods. Recently, the eddy covariance technique has been employed to determine the turbulent liquid water input to the ecosystems (e.g. Beswick et al., 1991; Vong and Kowalski, 1995; Kowalski et al., 1997). These studies have demonstrated the suitability of this technique for the direct measurement of turbulent liquid water fluxes.

Assuming the presence of a ‘constant flux layer’, the fluxes measured above the canopy are related to the sought-for surface fluxes. This implies that turbulent fluxes do not vary significantly with height within the surface layer (Prandtl, 1910), which is only valid for the momentum flux and also in close approximation for the fluxes of conservative entities (e.g. inert trace gases). However, fog or cloud droplets are not conservative entities; the turbulent flux of fog droplets, which can be referred to as the turbulent liquid water flux, is affected by phase change processes and coagulation. Thus, it needs to be examined whether under given conditions, the constant flux approach is also valid for the estimation of the fogwater deposited to a vegetation surface. For example, Kowalski and Vong (1999) performed liquid water flux measurements using the eddy covariance method on the crest of a forested ridge, situated at a distance of 3 km from the coastline of the Pacific Ocean. Fluxes measured at two levels on the same tower showed a persistent and significant flux divergence, i.e. the turbulent liquid water flux measured at the lower level exceeded the flux measured at the upper level. Consequently, Kowalski and Vong (1999) estimated that the measurements at the lower level underestimated the near-surface flux by 20–50%. They concluded that the observed divergence was due to advection and condensation during mean updrafts.

In this paper, results from a field campaign carried out in the Fichtelgebirge in northeastern Bavaria, Germany, are presented. The main emphasis is put on the experiences gained from an experiment in investigating the vertical flux divergence above the canopy.

2. Experimental

Between 18 September and 5 December 2000, two almost identical eddy covariance setups were operated simultaneously on a meteorological tower above the canopy of a spruce forest (*Picea abies*) at the Waldstein research site at 786 m a.s.l. (WFG). This site is described in detail in Wrzesinsky and Klemm (2000). During the first measuring period (hereafter denoted as ‘Comparison Experiment’ or CE), the two setups were operated at the same height on the top of the tower in order to evaluate and intercompare the instruments under identical environmental conditions (see Burkard et al., 2001a). During a second period (hereafter denoted as ‘Flux Divergence Experiment’ or FDE), the two setups were operated at different measurement heights to assess whether the constant flux approach is valid for deriving the surface fluxes of fogwater and ions dissolved therein. During CE, both setups were installed at 31.5 m a.g.l. During FDE (18/10–5/12/2000), the setups were mounted at 31.5 and 22 m a.g.l., which correspond to heights of 12.5 and 3 m above the top of the forest canopy, respectively. During both experiments, the two setups were automatically aligned with the mean wind direction every 30 min to minimize flow distortion.

2.1. Instrumentation

Both flux measurement setups consisted of a three-dimensional ultrasonic anemometer and an active high-speed FM-100 cloud particle spectrometer (Droplet Measurement Technologies, Boulder, CO, USA). A description of the FM-100 can be found in Thalmann et al. (2002), Eugster et al. (2001), and Burkard et al. (2001a). In contrast to earlier versions of the forward scattering spectrometer probes (FSSP), the FM-100 does not suffer from periods where no measurement activity takes place due to an electronic reset. Therefore, it is possible to continuously detect particles at a high sampling frequency, which is a prerequisite for deploying the eddy covariance method. A detailed description of this method for the present type of application can be found in Beswick et al. (1991). Both setups employed identical spectrometers, but the ultrasonic anemometers differed from each other. One setup included a Solent ultrasonic anemometer (model 1199 HSE with a built-in inclinometer, Gill, Solent, UK) which was operated at 12.5 Hz (hereafter denoted as setup S), whereas the other setup included a Young sonic anemometer (model 81000, R.M. Young, Traverse City, MI, USA) which was sampled at 8.9 Hz (hereafter denoted as setup G). Setup S was running during the entire measuring period while setup G was automatically switched-on only when the visibility (measured by a PWD11 present weather detector, manufactured by Vaisala Oy, Helsinki, Finland) was below 500 m.

2.2. Data processing

Turbulent fluxes were obtained by averaging the eddy covariance measurements over 30-min periods. Wind vector coordinates were rotated to align the main axis with the streamlines and to yield zero mean vertical wind. The linear trend was subtracted from all the scalar measurements before calculating the covariances.

At sites with higher wind speeds during fog (i.e. mountain stations), the change of the sample volume due to wind ramming must be considered (Choularton et al., 1986). In contrast to the older FSSPs, which required this correction, the FM-100 has a Pitot tube with a temperature transducer within the sample air flow just behind the sample area (SA) measuring the sample air flow speed U_s,

$$U_s = \sqrt{\frac{T_s}{1 + 0.2x^2}20.06x}, \tag{1}$$

where T_s is the sample temperature (in K) and x is determined from the measurements of the static and dynamic pressure (p and Δp, respectively),

$$x = \sqrt{4.9885\left[\left(1 + \frac{\Delta p}{p}\right)^{0.28565} - 1\right]}. \tag{2}$$

T_s, p, and Δp were measured with a resolution of 1 Hz. This computation of U_s is based on Bernoulli's principle, and the constants were tuned by the manufacturer to best fit true air speed. With U_s, the true sample volume SV is determined as $SV = SA \times U_s \times \Delta t$, where Δt is the elapsed time since the last data output, a variable recorded together with all the FM-100 data. This eliminates the requirement for the Choularton et al. (1986) correction (Darrell Baumgardner, personal communication).

To minimize flow distortion by the tower construction, all FDE data measured during periods with northeasterly to southerly wind directions (45–180°) were excluded from further analyses. Gravitational fluxes of liquid water were calculated using Stokes's settling velocity as described in Beswick et al. (1991).

The total flux F of fogwater is

$$F = \overline{w'\,c'} - V_s \bar{c}, \tag{3}$$

where w is the surface-normal wind component, c is the liquid water content (LWC), and V_s is the gravitational settling velocity. A prime denotes the instantaneous turbulent deviation of a measurement from its temporal mean (e.g. $w' = w - \tilde{w}$), and overbars denote temporal averages. The vertical flux divergence $\partial \overline{w'\,c'} / \partial z$ is

$$\frac{\partial \overline{w'\,c'}}{\partial z} = -\tilde{u}\frac{\partial \tilde{c}}{\partial x} - \frac{\partial \overline{u'\,c'}}{\partial x} - \frac{\partial \tilde{c}}{\partial t} + S_c, \tag{4}$$

where u is the streamwise wind component in x direction, z is the surface-normal direction perpendicular to the streamlines, t is the time axis, and S_c is the local source and sink term for liquid water. The four terms on the right hand side of Eq. (4) represent (i) the streamwise advection, (ii) the streamwise turbulent flux divergence, (iii) the storage term, and (iv) the local net source and sink term (i.e. condensation and evaporation of fog droplets). By aligning the coordinates with the mean streamlines, $\bar{w}$ is forced to be zero, and the term "vertical" therefore corresponds to the surface-normal direction.

3. Results

During CE, 20 fog events with a total of 162 h of fog were observed. The non-parametric Mann–Whitney test indicated that the LWC measurements of the two FM-100 in use agreed statistically well ($P < 0.05$) during the 7 out of 20 fog events. In the course of the remaining 13 events, technical problems occurred such as electronic glitches, or one setup was not well aligned with the mean wind direction. An example of a good agreement between the two measurements setups after intercalibration is shown in Fig. 1, although differences in the gravitational fluxes were initially observed due to the much higher droplet counts measured by the FM-100 of setup G. In order to check the accuracy of the FM-100 sensor of setup S, it was intercompared with a Particle Volume Monitor (PVM, manufactured by Gerber Scientific, Reston, VA, USA). The principle of operation of the ground-based version of the PVM is described in detail in Gerber (1984, 1991). During an experiment in Switzerland in winter 2001/2002, both instruments were operated simultaneously above a forest canopy. The results of this intercomparison experiment showed good agreement between these two devices with $r^2 = 0.887$, a slope of 0.825 ± 0.008 (mean ± SE), and an intercept of 2.96 ± 0.747 mg m^{-3} on the basis of 10-min averages,

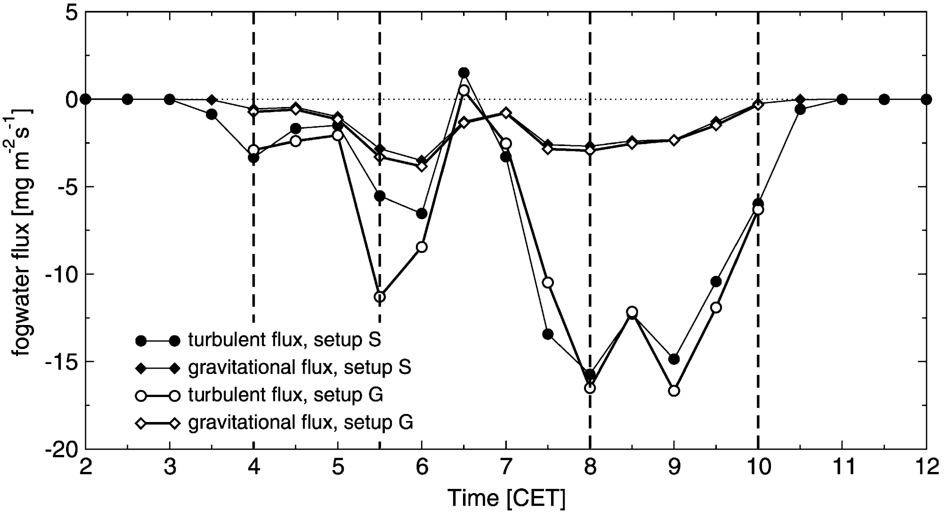

Fig. 1. Turbulent and gravitational liquid water fluxes in mg m^{-2} s^{-1} during the fog event of 28 September 2000 (intercomparison experiment CE), 02:00–12:00 CET (half-hour averages). Negative values indicate a downward transport of liquid water. Broken vertical lines indicate the times of the selected droplet spectra displayed in Fig. 2.

where the PVM is the independent variable. Most likely, the differences between the PVM and FM-100 measurements are due to the different response characteristics (Wendisch, 1998) and the fact that the PVM was not always facing the wind. Being aware of the remaining uncertainties in the absolute values from both the PVM and the FM-100, it was decided to use setup S as a reference for the present analyses and adjust the gravitational, the turbulent fluxes, and LWC from setup G using a scaling factor of 0.5 in all figures and analyses presented here. In the case of the turbulent fluxes, an additional scaling factor for differences in sonic anemometers (*w* differed by a factor of 2.0; cf. Eugster et al., 2001) was used to correct fluxes of setup G.

After these corrections, the agreement between the two FM-100 devices is excellent with respect to the measured LWC as a function of the mean droplet diameter (Fig. 2). The turbulent liquid water fluxes measured by setup S and G also agree very well for fluxes > -9 mg m^{-2} s^{-1} ($r^2 = 0.747$ with a slope of 0.990 ± 0.032), but this correlation, and hence the confidence in the measurements, decreases with increasing negative fluxes. Given the overall good agreement of the turbulent fluxes (-4.76 ± 0.32 and -4.32 ± 0.27 mg m^{-2} s^{-1} for setup S and G, respectively), no corrections other than the scaling factors were applied to the turbulent liquid water fluxes measured during CE and FDE.

The comparison between spectra and cospectra of the fog events that passed our data selection criteria also showed good agreement between the two setups. Although some differences in the spectral behavior of the corresponding instruments were found, the results are not significantly biased and therefore no correction is required. Fig. 3A indicates the good agreement between the normalized turbulent fluxes during CE. At

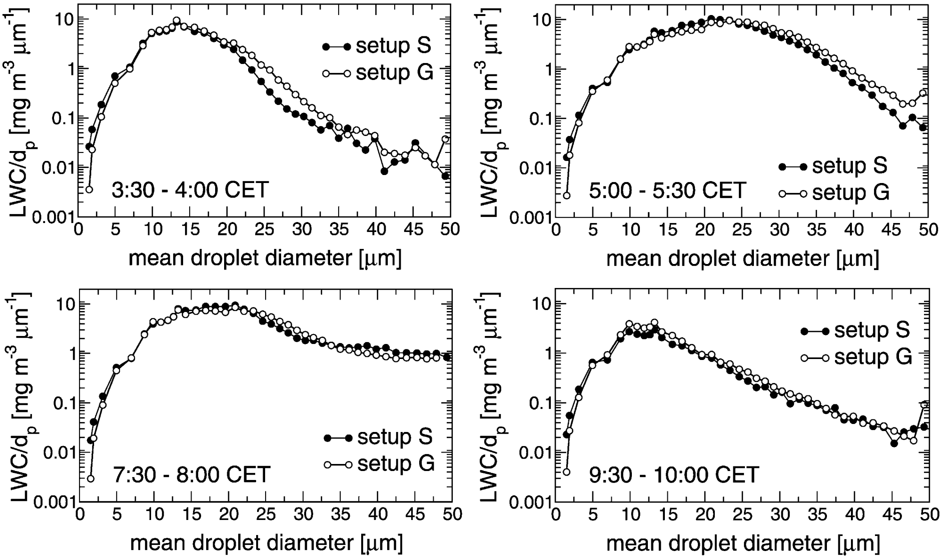

Fig. 2. Liquid water content per unit droplet diameter (mg m^{-3} µm^{-1}) during four characteristic 30-min time intervals as a function of the mean droplet diameter during the fog event of 28 September 2000.

frequencies >0.2 Hz, the cospectra closely follow the expected inertial subrange slope ($f^{-4/3}$) despite the significant noise levels at high frequencies of the LWC variance spectrum (not shown). This is no surprise since random noise is not correlated with turbulent fluctuations, and the high frequency contribution is much less important for covariances than it is for variances.

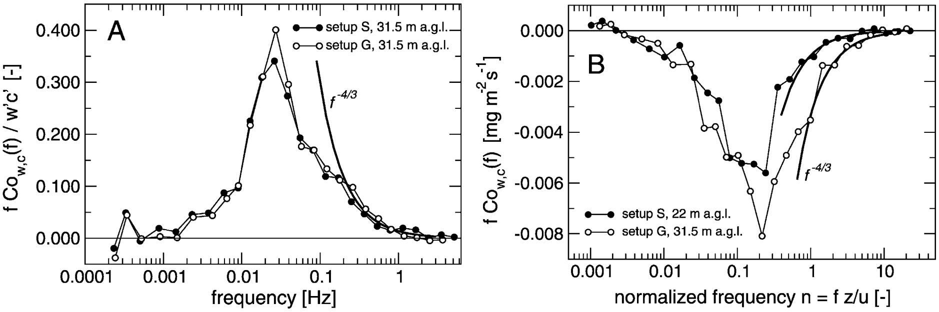

Fig. 3. Cospectra of turbulent liquid water fluxes (A) measured with two instruments at 31.5 m a.g.l. over the period of 7:00–10:00 CET during the fog event of 28 September 2000 (intercomparison experiment CE), and (B) measured at different heights of 22 (setup S) and 31.5 m a.g.l. (setup G) over the period of 15:00–18:00 CET during the fog event of 28 November 2000 (FDE). Cospectral densities were normalized and depicted as a function of the natural frequency f in panel (A), while absolute densities as a function of the normalized frequency $n = fz/\bar{u}$ are shown in panel (B) to allow for the best possible comparison in both cases.

During FDE, a total of 22 fog events passed our data selection criteria, which corresponds to 215 h of fog occurrence. During all of the fog events, the intercalibrated LWC measured at the upper level of the tower was on the order of the LWC measured at the lower level (Fig. 4A). The turbulent liquid water fluxes at the upper level exceeded the fluxes at the lower level (Fig. 4B), while there were no significant differences in the gravitational fluxes. The contribution of the gravitational fluxes to the total liquid fogwater fluxes was relatively small (approximately 10%) for both measurement heights. Therefore, the difference in the turbulent fluxes appears to be the most relevant, implying that the fogwater fluxes determined at a single measurement height above a forest canopy differ from the true canopy interception.

As a case study, one selected fog event is described in more detail. During the afternoon of the 28 November 2000, a fog event with a duration of 9 h was observed. Monin–Obukhov length computations confirm that the atmospheric conditions were nearly neutral ($-0.138 \leq z/L \leq 0.032$). Humid air masses from the SW were advected to the site. Low net radiation (between 0 and 20 W m^{-2}; data not shown) and visibility measurements (Fig. 5A) indicate that there was a dense fog layer with negligible influence of convection and entrainment. Measured wind profiles agree well with a logarithmic wind profile, indicating that the fetch during this fog event was ideal (not shown). During the whole event, LWC and gravitational flux at 31.5 m a.g.l. were in close agreement with the values observed at 22 m a.g.l. (Fig. 5). Large differences were found in the measured turbulent liquid water fluxes, although the shape of the two curves are quite similar (Fig. 5B). A detailed examination of the cospectrum of the period with the largest downward fluxes (Fig. 3B) suggests that the flux divergence does not affect low normalized frequencies $n < 0.1$. On the high-frequency end, the cospectra from both measurement heights closely

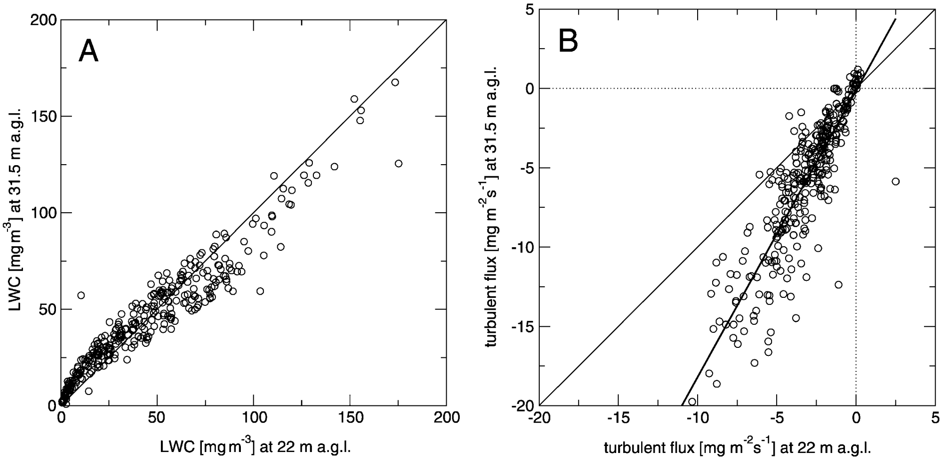

Fig. 4. Comparison of half-hourly averaged (A) intercalibrated liquid water content (LWC), and (B) turbulent liquid water fluxes at 22 (setup S) and 31.5 m a.g.l. (setup G). Thin lines indicate the 1:1 ratio, and the bold line in panel (B) indicates the linear regression of the observed fluxes > -20 mg m^{-2} s^{-1} during FDE with $r^2 = 0.746$.

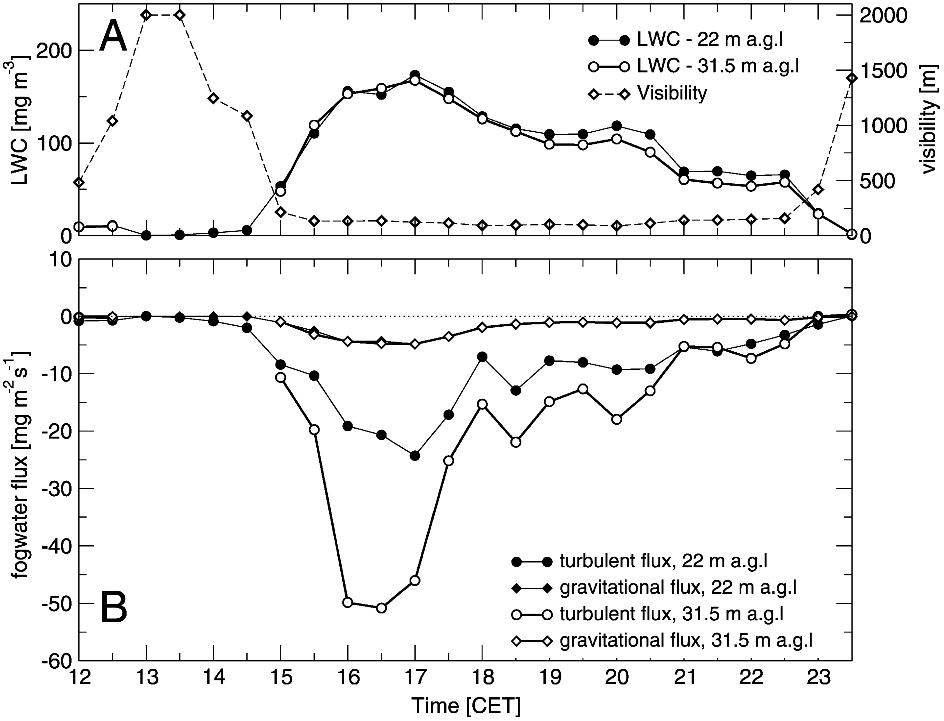

Fig. 5. Fog event of 28 November 2000, 12:00–23:30 CET (half-hour averages). (A) Liquid water content in mg m^{-3} at 31.5 and 22 m a.g.l., respectively, and visibility in meters (right y-axis). (B) Turbulent and gravitational liquid water fluxes in mg m^{-2} s^{-1} during the fog event of 28 November 2000, 12:00–23:30 CET (half-hourly averages).

follow an $f^{-4/3}$ power law as can be expected in the inertial subrange of the cospectrum. This indicates that the flux divergence is due to some process which acts on the intermediate energy-containing range of the cospectrum, and this difference cascades down the inertial subrange as expected from the turbulence theory; hence, the difference of a factor of 3.5 in the inertial subranges in Fig. 5B. This suggests that neither the averaging interval of 30 min nor the proximity to the canopy is the primary explanation for the flux divergence.

Via the angular data of the Solent HS ultrasonic anemometer's built-in inclinometer (setup S at 22 m a.g.l.), it was possible to calculate the mean vertical wind speed parallel to the gravity vector with high accuracy in order to investigate whether lifting processes might explain the observed vertical flux divergence. The mean updraft during this event was 0.053 ± 0.007 m s^{-1}, compared to a horizontal component of 2.11 ± 0.049 m s^{-1}, indicating that the angle between the streamlines and horizontal plain was only 1.4°. By choosing the streamline coordinates, the surface-normal advection $\tilde{w}\partial\tilde{c}/\partial z$ was forced to be zero, but even in the geopotential reference frame, the observed small updraft velocity and small LWC gradient support the assumption that vertical advection is not the main cause of the observed vertical flux divergence.

4. Discussion

4.1. Data quality

Although the two setups had different sampling frequencies and included different ultrasonic anemometers, the results of CE are encouraging. In the literature, the eddy covariance method is often described as the only direct flux measurement technique. However, there is no universal statistical approach for testing the quality of the flux data directly. In the case of our experiment, the quality of the two time series involved in the flux computation, and accordingly the two instruments (ultrasonic anemometer and the FM-100), can be independently checked. One approach is to check the data quality by comparing the observed ratio between the standard deviation of the vertical wind speed and the friction velocity with idealized curves taken from Panofsky et al. (1977). Foken and Wichura (1996) suggested that deviations of less than 20–30% from such an idealized curve indicated good data quality. For both setups, 95% of the data were within ± 30% from the ideal curve and hence can be considered to be of good quality. In case of setup S, most values were even within a narrow range of ± 15%. Moreover, spectral analyses of the FM-100 data of both setups showed a very good agreement with the theoretical spectra published by Kaimal et al. (1972) in the high-frequency range. This indicates a high quality of the FM-100 measurements of both setups. The analyses of the turbulent flux data by Eugster et al. (2001) showed that despite the relatively high noise level observed with the FM-100 instruments, the turbulent fogwater flux measurements were estimated to be accurate within ± 0.63 mg m^{-2} s^{-1}, although this does not imply that the absolute flux densities are of very high precision. Eugster et al. (2001) concluded that both setups produced reliable flux measurements during periods where the instruments were operated properly.

4.2. Flux divergence experiment

Based on the experience gained during the intercomparison, the reliability and accuracy of our measurements are assumed to be sufficient to compare data measured during the FDE with the two setups at different heights. It should be noted that no technical problem occurred during the FDE (Burkard et al., 2001b).

Our measurements during the FDE revealed a persistent negative turbulent liquid water flux divergence. According to Eq. (4), there are several terms that could potentially explain this flux divergence. Averaged over an entire fog event, the storage term $\partial\tilde{c}/\partial t$ becomes zero. It is then assumed that the streamwise turbulent flux divergence is small compared to the streamwise advection term, and thus can be neglected. This means that the streamwise advection and net source or sink term remain as the two potential explanations, either exclusively or in combination.

4.3. Alternative explanations

An alternative interpretation would be that setup S was installed too close to the forest canopy. Kaimal and Finnigan (1994) showed with profiles of various turbulence parameters that there is a strong difference between the turbulence within the canopy (e.g. near canopy layer) and the layer above. In our case, the average friction velocities u_* do not indicate a large difference between the two measurement heights. Mean u_* during the 22 FDE fog events was 0.62 ± 0.01 and 0.65 ± 0.011 m s^{-1} at 22 and 31.5 m a.g.l., respectively, which is within the experimental uncertainty of u_* (see Geissbühler et al., 2000). Accordingly, we deduce that the lower setup was installed at a height with sufficient distance from the canopy. Hence, this fact cannot explain the observed flux divergence, but rather suggests that the fogwater fluxes measured at both measurement heights should be similar, unless one or more terms in Eq. (4) behave differently for liquid water fluxes than for momentum flux. Kowalski and Vong (1999) concluded that the vertical flux divergence they observed was related to the condensation of the water due to the updrafting winds, and thus was due to liquid water advection. As argued above, vertical advection does not account for the observed vertical flux divergence in our case.

Initially, a step change in the canopy height of roughly 4 m due to a different forest management at a distance of about 100 m from the tower was thought to be responsible for the observed vertical flux divergence. However, our results indicate a much more systematic and larger difference between the measurements at different heights. Additionally, the lack of significant differences in u_* and z_0 (geometric means of 2.9 and 2.8 m at the upper and lower level, respectively, during FDE), which were determined at the two heights, suggests that this change in canopy height does not significantly alter the turbulence field at our site. Mean atmospheric transfer resistances $R_a = \tilde{u}/u_*^2$ during CE were 12.3 ± 0.4 and 15.5 ± 0.6 s m^{-1} for setup S and G, respectively. During FDE, R_a averaged at 6.4 ± 0.5 and 11.5 ± 2.3 s m^{-1}, respectively, which corresponds to the ratio of measuring the heights above the displacement heights (9.3 and 18.8 m, respectively). Turbulent deposition velocity $v_t = -F_c/\tilde{c}$ was close to the theoretical maximum $v_{t,\max} = 1/R_a$. Average v_t was 0.078 ± 0.008 and 0.043 ± 0.005 m s^{-1} during CE, and 0.101 ± 0.004 and 0.070 ± 0.003 m s^{-1} during FDE for setup S and G, respectively. Since $R_a \propto z$, these results indicate that the differences observed during FDE are a simple function of the measurement height, and that the step change can be ruled out to be the cause for the vertical flux divergence.

4.4. Most likely interpretation

Based on these considerations, the streamwise advection and/or net source and sink term must be regarded responsible for the vertical flux divergence. Net evaporation is very likely to contribute, at least partially, to the flux divergence. As the fog droplets grow due to condensation and coagulation, they reduce the ambient air humidity at both measurement heights. During the lifetime of a fog layer, the droplets continue to grow (primarily due to coagulation) and become subject to sedimentation and increased turbulent downward transport, while the smaller fog droplets in their vicinity evaporate because of the lowered humidity (Houze, 1993). Considerations based on the collision efficiency of fog droplets in turbulent air (e.g. Pruppacher and Klett, 1998, p. 590) using measured turbulent dissipation rates (0.037 and 0.064 m^2 s^{-3} at the upper and lower level during FDE, respectively) suggest that the peak in the droplet size spectrum would shift from 20 to 200 μm in diameter within less than 10 min in an undisturbed fog chamber. Such a shift, however, was not observed at our site, and may be an indication that the net evaporation (the difference between evaporation and concurrent condensation) of droplets is very strong and keeps the peak in the droplet size spectrum relatively unchanged (Fig. 2). At the same time, the stable peak is an indication that streamwise advection is much less important than the evaporation of droplets. If this assumption is true, the constant flux approach could be used to determine the ion fluxes to a forest by the eddy covariance method, although the constant flux assumption would not hold for the flux of liquid water itself. The reason for this is that the absolute amount of ions is conserved in the droplets contained in a fixed volume of air even when the droplets shrink due to evaporation, i.e. ion concentrations in fogwater increase as the liquid water concentration decreases due to evaporation, while their product—also known as cloudwater loading—remains unchanged (Junge, 1963). This assumption was found to hold for a wide variety of sites (Elbert et al., 2000). Although questioned recently by Kasper-Giebl (2002), there are good reasons to assume that in nonremote areas, such an assumption is defensible (Elbert et al., 2002).

In the case of liquid water fluxes, an observed flux divergence of -0.349 mg m^{-3} s^{-1} was used to extrapolate measurements to the canopy top. In this case, the turbulent and gravitational liquid water input to the forest canopy during FDE was 232 and 26 g m^{-2} day^{-1}, respectively. The universal factor to extrapolate the turbulent liquid water flux measured at height z to the canopy top at height h_c is thus $1/[1+0.116(z-h_c)]$ if the flux divergence is assumed to be constant with height and proportional to the turbulent flux at the canopy top $F(h_c)$. It should, however, be noticed that this first-order extrapolation does not consider the height dependency of differences in the droplet size spectra, water vapor concentration, and droplet evaporation.

4.5. Recommendations for future studies

Future experiments should investigate the time evolution of the stable isotope ratios δD and δ^{18}O in fog water. Net evaporation is expected to leave a distinct imprint due to the isotope fractionation process, where the lighter isotopes, H and ^{16}O, escape more easily from the droplets, while streamwise advection should not change the isotope signature of fogwater.

Furthermore, it must be emphasized that the use of sonic anemometers of different brands and makes introduced considerable additional uncertainty to our study, especially due to the experience that the instrument used in setup G did not reveal research quality performance and reliability. To reduce this remaining uncertainty, only high-quality research grade sonic anemometers should be used in future studies.

5. Conclusions

During a field experiment at the Waldstein research site in autumn 2000, a persistent negative flux divergence was observed during all fog events. Possible explanations have been discussed: (a) measurements of one of the two (or both) eddy covariance setups are inaccurate; (b) the lower setup is too close to the canopy; (c) differences in the surface influence the flux measurements at the two heights; and (d) streamwise advection and/or net evaporation of droplets. Statistical tests of the turbulence and FM-100 data showed good quality and agreement between the two setups after intercalibration when running simultaneously at the same height. It is argued that the net evaporation of droplets is most likely to be the cause of the observed vertical flux divergence. This implies that the constant flux approach is not strictly valid for extrapolating fogwater flux measurements to the canopy surface. However, if evaporation is the dominant process, then the ion flux inferred from the eddy covariance fogwater flux measurements can still be regarded as the representative for the canopy surface since the evaporation of droplets does not change the absolute amount of dissolved ions in the fogwater deposited to the canopy. In order to determine the relative importance of streamwise advection, condensation, and evaporation in future experiments, it is suggested to investigate the temporal evolution of the stable isotope signature in fogwater which makes it possible to discriminate between these most probable processes leading to vertical flux divergence.

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References

Beswick, K.M., Hargreaves, K.J., Gallagher, M.W., Choularton, T., Fowler, D., 1991. Size-resolved measurements of cloud droplet deposition velocity to a forest canopy using an eddy correlation technique. Quarterly Journal of the Royal Meteorological Society 117, 623–645.

Burkard, R., Wrzesinsky, T., Eugster, W., Klemm, O., 2001a. Quantification of fog deposition with two similar set-ups. In: Schemenauer, R., Puxbaum, H. (Eds.), Proceedings of the Second International Conference on Fog and Fog Collection, St. John's, Canada, 15–20 July 2001, pp. 185–188.

Burkard, R., Wrzesinsky, T., Eugster, W., Klemm, O., 2001b. Vertical flux divergence during fog deposition. In: Schemenauer, R., Puxbaum, H. (Eds.), Proceedings of the Second International Conference on Fog and Fog Collection, St. John's, Canada, 15–20 July 2001, pp. 161–164.

Choularton, T.W., Consterdine, I.E., Gardiner, B.A., Gay, M.J., Hill, M.K., Latham, J., Stromberg, I.M., 1986. Field studies of the optical and microphysical characteristics of clouds enveloping Great Dun Fell. Quarterly Journal of the Royal Meteorological Society 112, 131–148.

Elbert, W., Hoffmann, M.R., Krämer, M., Schmitt, G., Andreae, M.O., 2000. Control of solute concentrations in cloud and fog water by liquid water content. Atmospheric Environment 34, 1109–1122.

Elbert, W., Krämer, M., Andreae, M.O., 2002. Reply to discussion on "control of solute concentration in cloud and fog water by liquid water content". Atmospheric Environment 36, 1909–1910.

Eugster, W., Burkard, R., Klemm, O., Wrzesinsky, T., 2001. Fog deposition measurements with the eddy covariance method. In: Schemenauer, R., Puxbaum, H. (Eds.), Proceedings of the Second International Conference on Fog and Fog Collection, St. John's, Canada, 15–20 July 2001, pp. 193–196.

Foken, T., Wichura, B., 1996. Tools for quality assessment of surface-based flux measurements. Agricultural and Forest Meteorology 78, 83–105.

Geissbühler, P., Siegwolf, R., Eugster, W., 2000. Eddy covariance measurements on mountain slopes: the advantage of surface–normal sensor orientation over a vertical set-up. Boundary-Layer Meteorology 96, 371–392.

Gerber, H.E., 1984. Liquid water content of fogs and hazes from visible light scattering. Journal of Climate and Applied Meteorology 3, 1247–1252.

Gerber, H.E., 1991. Direct measurement of suspended particulate volume concentration and far-infrared extinction coefficient with a laser-diffraction instrument. Applied Optics 30, 4824–4831.

Houze, R.A., 1993. Cloud Dynamics. Academic Press, San Diego, CA.

Junge, C.E., 1963. Air Chemistry and Radioactivity. Academic Press, New York.

Kaimal, J.C., Finnigan, J.J., 1994. Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford Univ. Press, New York.

Kaimal, J.C., Wyngaard, J.C., Izumi, Y., Coté, O.R., 1972. Spectral characteristics of surface layer turbulence. Quarterly Journal of the Royal Meteorological Society 98, 563–589.

Kasper-Giebl, A., 2002. Control of solute concentrations in cloud and fog water by liquid water content. Atmospheric Environment 36, 1907–1908.

Kowalski, A.S., Vong, R.J., 1999. Near-surface fluxes of cloud water evolve vertically. Quarterly Journal of the Royal Meteorological Society 125, 2663–2684.

Kowalski, A.S., Anthoni, P.M., Vong, R.J., Delany, A.C., Maclean, G.D., 1997. Deployment and evaluation of a system for ground-based measurement of cloud liquid water turbulent fluxes. Journal of Atmospheric and Oceanic Technology 14, 468–479.

Panofsky, H.A., Tennekes, H., Lenschow, D.H., Wyngaard, J.C., 1977. The characteristics of turbulent velocity components in the surface layer under convective conditions. Boundary-Layer Meteorology 11, 355–361.

Prandtl, L., 1910. Bericht über Untersuchungen zur ausgebildeten Turbulenz. Zeitschrift für angewandte Mathematik und Mechanik 5, 136–139.

Pruppacher, H.R., Klett, J.D., 1998. Microphysics of Clouds and Precipitation. Kluwer Academic Publishing, Dordrecht.

Thalmann, E., Burkard, R., Wrzesinsky, T., Eugster, W., Klemm, O., 2001. Ion fluxes from fog and rain to an agricultural and a forest ecosystem in Europe. Atmospheric Research 64, 133-145.

Vong, R.J., Kowalski, A.S., 1995. Eddy correlation measurements of size-dependent cloud droplet turbulent fluxes to complex terrain. Tellus 47B (3), 331–352.

Wendisch, M., 1998. A quantitative comparison of ground-based FSSP and PVM measurements. Journal of Atmospheric and Oceanic Technology 15, 887–899.

Wrzesinsky, T., Klemm, O., 2000. Summertime fog chemistry at a mountainous site in central Europe. Atmospheric Environment 34, 1487–1496.