MiniCASCC – A Battery Driven Fog Collector for Ecosystem Research

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Abstract

We developed a small version of the Caltech active strand cloud water collector (CASCC) for biogeochemical investigations in ecological applications. The device is battery powered and thus allows operation at locations where mains power is not available. The collector is designed for sampling periods of up to one week, depending on fog frequency. Our new device is equipped with standard sensors for air temperature, relative humidity, wind, and horizontal visibility for fog detection with a low-cost optical sensor. In mountain areas and during times when clouds are thin the installation of the visibility sensor became a key issue, which limits the potential to estimate liquid water content of the sampled fog. Field tests with 5 devices at three different sites in the Swiss Alps (Niesen) and the Jura Mountains (Lägeren, Switzerland) during two extended summer seasons in 2006 and 2007 showed that in almost all cases it was possible to obtain sample volumes which were large enough for the examination of basic inorganic chemistry of the collected cloud water. Collection rates varied typically from 12 to 30 mL h\textsuperscript{−1}. The fog droplet cutoff diameter is ≈ 6 µm, which is low enough to include all droplet sizes that are relevant for the liquid water content of typical fog types in the collected samples. From theoretical assumptions of the collection efficiency and theoretical droplet spectra it is possible to estimate the liquid water content of the sampled fog or cloud. Our new fog collector can be constructed and operated at relatively low costs. In combination with chemical and isotopic analyses of the sampled water, this allows to quantify nutrient and pollutant fluxes as is typically needed in ecosystem biogeochemistry studies.
Highlights:

- A small version of the Caltech active strand cloud water collector was developed
- The collector is useful to determine nutrient and pollutant fluxes to ecosystems
- Collection rates varied typically between 12 and 30 mL h\(^{-1}\) during fog events
- The design allows to collect samples at remote sites and in mountain areas
- The collector is battery driven and allows sampling of weekly bulk samples

Keywords: Cloud water collector, Fog chemistry, Cloud chemistry, Stable isotopes, Droplet sampler
1. Introduction

Collecting sufficient amounts of fogwater for the analysis of solutes and stable isotopes is an important problem with fog research at remote sites without mains electricity. Passive fog collectors (e.g. used by Schemenauer et al. 1995 or Lange et al. 2003) solve the problem with unavailable electricity at the site. However, their collection characteristics are not specific for fog droplets, but may also be contaminated by unknown amounts of drizzle, horizontal wind-driven (e.g., Schmid et al. 2011) and conventional precipitation (measured by a standard rain gauge). Moreover, the cut-off diameter—that is, the droplet size threshold below which more than 50% of the droplets are not captured by the device—strongly depends on ambient wind speed across passive fog collectors. Thus, for scientific studies where the chemistry or isotopic composition of fogwater is compared with that of rain water, the Caltech active strand cloud water collector (CASCC, Daube et al. 1987) has become the preferred sampling instrument in many studies (e.g., Collett et al. 1989; Klemm et al. 1994; Collett et al. 1999; Hoag et al. 1999; Wrzesinsky and Klemm 2000; Anastasio and McGregor 2001; Collett et al. 2002; Thalmann et al. 2002; Ervens et al. 2003; Lu et al. 2010). Large collectors of the CASCC type are described e.g. in Fuzzi et al. [1997], Minami and Ishizaka [1996], and Sasakawa and Uematsu [2002] who all used very similar sampling devices. Further developments include the multistage collectors that resolve 2 or more size fractions (sf-CASCC; e.g. Bator and Collett 1997; Collett et al. 1989; Reilly et al. 2001) and a smaller CASCC2 [Demoz et al., 1996]. Alternative techniques were used by Straub and Collett [2002], and Moore et al. [2002] who used a 5-stage cascade rectangular jet impactor for cloud and fog droplet sampling. A good overview of existing collectors of the CASCC type is given by Demoz et al. [1996].

The drawback, however, is the relatively high power consumption of this sampler type and hence its deployment is limited to sites that provide mains power, or are close to a road (e.g., Collett et al. 1989) to minimize transport distances for batteries. In the few cases where they were operated on battery power, logistical restrictions limited the selection of sites to those close to access roads. For ecological applications it would however be essential to overcome such logistic constraints. This requires a yet smaller collector that can operate during a period of about one to
two weeks without mains power. Electricity can be provided by one or two standard car or marine
deep cycle batteries. Strapped to a backpack, these can be carried by one strong person over longer
distances from the nearest access road (or summit station). To achieve this, we developed a new
variant of the CASCC, named MiniCASCC, the smallest active cloudwater collector so far, which
also allowed us to further reduce material costs for building the device. The aim of this paper is to
present its design and performance under both controlled and field conditions.

2. Methods

2.1. Efficiency Considerations

Demoz et al. [1996] have provided a comprehensive overview on the theoretical concepts of the
Caltech active strand cloudwater collectors (CASCC). They showed that the collection efficiency
of these types of collectors varies with drop size. Here, we briefly summarize the considerations
made by Demoz et al. [1996] and show how this theoretical framework provides the basis for a
low-power variant of the CASCC.

The collection efficiency of a single strand can be expressed in terms of the dimensionless
Stokes number, which is defined as

\[ St = \frac{\rho d_p^2 U \cos \theta}{9 \mu d_c}, \]  

(1)

where \( \rho \) is the droplet density, \( d_p \) the droplet diameter, \( U \) the air speed, \( \theta \) the inclination angle of the
bank of strands from vertical, \( \mu \) the air viscosity and \( d_c \) the diameter of the strand. Further, Demoz
et al. [1996] used the equation by Davidson and Friedlander [1978] to calculate the efficiency \( \eta_s \)
of the strands to collect fog droplets. The equation is given in terms of the Stokes number as

\[ \eta_s = \frac{St^3}{St^3 + 0.753St^2 + 2.796St - 0.202}. \]  

(2)

They provide the theoretical collection efficiency for each collector stage (as total efficiency of the
bank of strands) then as

\[ \eta = 1 - (1 - \eta_s \times fr)^r, \]  

(3)

with \( fr \) as fractional coverage per row (cross-sectional area of the strands in a row divided by the
total cross sectional area of the collector), and \( r \) as number of rows.
Figure 1 shows the collection efficiency as a function of air speed ($U$), number of rows ($r$), strand diameter ($d_c$) and strand spacing ($d_s$), compared to the CASCC2 as shown in Demoz et al. [1996].

The overall calculated efficiency depends strongly on the number of rows, diameter of the strands and the strand spacing. Whereas one row reaches an efficiency of less than 25%, six rows (as used in the CASCC2) are predicted to collect with an efficiency of over 80% for droplets exceeding 10 µm in diameter [Demoz et al., 1996]. Similar results were found for the strand diameter and the strand spacing. An important characteristic of this set of curves is a pronounced cutoff around 5 µm (at an air speed of 8 m s$^{-1}$), which means that these factors (i.e., strand diameter, strand spacing, and number of rows) control the overall efficiency of the collector and do not introduce an unwanted size-fractionation of the droplet spectrum, i.e., that the large droplets are preferentially collected. The fourth considered factor, the air speed at the strands, shows a different behaviour compared to the previous three factors. For low air speeds ($U < 2$ m s$^{-1}$) a substantial size-fractionation is expected, which could have negative effects on solute and stable isotope concentrations in the samples in cases when they depend on drop size. In theory, this should not be the case for stable isotopes in water [Spiegel et al., 2012a], but can be relevant in the case of solutes [Bator and Collett, 1997; Collett et al., 1993, 1994; Schell et al., 1997; Moore et al., 2004a,b].

In principle, it would be desirable to collect all relevant droplet sizes with one single-stage MiniCASCC. Hence, from the four factors mentioned above it is the air speed at the strands which is the most important factor to control the size-fractionation of droplets collected on the strands. This implies that great care must be given to the air speed which must reach a sufficiently high value, whereas the remaining three factors (strand diameter, strand spacing and number of rows) can be selected from a wide range of possibilities without significantly changing the cutoff diameter. A reasonable value for our application therefore must be above 4 m s$^{-1}$, since most droplets in fog are in the range 5–35 µm [Pruppacher and Klett, 2010; Bruijnzeel et al., 2005].
2.2. Dimensions of the Device

The requirement of high air speed across the strands is most easily achieved by a small cross-section of the sampling device, since power consumption by fans tend to increase with size if air flow per unit cross-section area is kept constant. At the same time, the cross section cannot be too small since a smaller cross section reduces the amount of fogwater that can be collected per unit time, all other factors kept constant. A third factor to be considered is the cost of the device; our evaluation indicated that if standard high performance fans used to ventilate computers can be used, then costs of the fan alone are much lower than if large fans are used. The typical largest size of such fans that meet the power consumption requirements are $12\times12\,\text{cm}^2$ in size, and hence we aimed at a nominal inner cross section of $10\times10\,\text{cm}^2$ of the MiniCASCC. We used PELKO R1238Y12BPLBx fans (Shang Hai Ke Chang Electronics Co., Ltd., China).

The target volume of fogwater collected per event was set to $\geq 30\,\text{mL}$, which was the typical requirement for all chemical and isotopic analyses plus standard conductivity and pH measurements. The volume requirements of a standard liquid ion chromatograph is typically no more than 25–200 $\mu\text{L}$ and even less is needed for stable isotope measurements on an isotope ratio mass spectrometer (on the order of 0.5 $\mu\text{L}$). Hence, in cases where fogwater is expected to be so clean that no filtering is needed, our design of the MiniCASCC could still be further optimized. In our specific case, however, the requirements for conductivity and pH measurements were the most critical ones which led to the 30 mL collection target specification for the MiniCASCC.

To achieve this, a realistic estimate for liquid water content (LWC) of the fog must be available. We based our calculation on typical values in the range 25 to 200 mg m$^{-3}$ (geometric mean 70 mg m$^{-3}$) that Bützberger [2002] found at the Lägeren site, Switzerland, in fog under advective influence from mid of September 2001 to mid of April 2002. This range of values is also expected to be valid for the type of fog which occurs most frequently during summer in Switzerland, but which has not been systematically investigated in the past. A second empirical estimate was available from the Fichtelgebirge, Germany, where Wrzesinsky and Klemm [2000] used a CASCC type fog collector with a flow rate of 1150 m$^3$ h$^{-1}$. They reported fogwater collection rates between 6.6 and 432 mL h$^{-1}$ (mean of 90 mL h$^{-1}$), which translates to LWC in the range 7 to 470 mg m$^{-3}$ (mean 98 mg m$^{-3}$) if an estimated collection efficiency of 0.8 is used.
Since the critical issue is to obtain enough water during weak fog events of short duration, we computed the required air speed in a device with 6 strand rows (as in the CASCC2; Demoz et al. 1996) for a fog event of 5 h duration at a low LWC of 50 mg m$^{-3}$. At an assumed overall collection efficiency of 0.8 a fan with an airflow $> 250 \text{ m}^3\text{ h}^{-1}$ is needed. Consequently, the air speed must be $\geq 4.17 \text{ m s}^{-1}$ for a $10\times10 \text{ cm}^2$ inlet. Table 1 summarizes the characteristics of the CASCC, CASCC2, and the new MiniCASCC.

[Table 1 about here.]

2.3. Collector Construction and Operation

The MiniCASCC can be divided into three units, namely the collector itself, the boom for mounting the meteorological sensors and a panel box (Figure 2). The instrument boom has a length of 1.5 m and holds the wind speed/direction monitor and the thermo-hygrometer.

[Figure 2 about here.]

The collector tube itself consists of 4 components: (1) a rain shield, followed by (2) the collection unit with the strands and the water outlet, (3) a 7.5 cm long honeycomb element unit to prevent turbulence inside the tube, and (4) the fan unit. Each of these units can be replaced separately in the field. We used stainless steel with a plexiglass insert containing the teflon strands, but the entire device could be built with plexiglass.

The panel box contains the data logger with control electronics, batteries, and the sample reservoir. All external sensor connections were guided through an overvoltage protection for minimizing the lightning damage risk. External sensors were used to switch the collector on and off (see Section 2.4).

The collector has a $10\times10 \text{ cm}^2$ profile and a total length of 90 cm. Air is drawn by a fan with a nominal performance of 280 m$^3\text{ h}^{-1}$ (actually measured: $\approx 150 \text{ m}^3\text{ h}^{-1}$; see Section 3.2) through six rows of 0.5 mm diameter teflon strands with a spacing of 2.0 mm, and an inclination angle of 35°. The resulting (nominal) air speed equals to 7.8 m s$^{-1}$, which is expected to be lower in reality due to aerodynamic drag inside the collector tube. The collected water drips from the bottom of
the strands into a teflon funnel and through a teflon tube into the sample reservoir, a 2.0 L glass bottle. The sample reservoir is closed with a pinch valve to minimize evaporation of the fogwater during non-fog conditions. Glass bottles were chosen because they are considered best for stable isotope analysis, but in the future, plastic bottles (e.g. Teflon or HDPE) shall be used which are better suited for chemical analyses, whereas their effect on isotopic samples is not much different from that of glass for short-term storage [Mook, 2000].

We equipped the fog collectors with two 12 V/36 Ah valve regulated lead-acid batteries with a total 72 Ah capacity (C20 capacity, which indicates the useable capacity if the battery shall be drained in 20 hours at a temperature of 20 °C). With a power consumption of \( \approx 1.5 \) A, the device can collect fog during \( \approx 48 \) h. The standby power consumption is around 0.3 A, corresponding to a standby period of \( \approx 240 \) h (10 days). In both cases, the power draw is less than the C20 reference, and hence the true time of operation is expected to be even longer than what the theoretical computations suggests, when the battery is new. Lower temperatures reduce the usable capacity of a battery. Hence we tested battery performance in the field. Our tests were performed at a mean ambient temperature of 8.7 °C which allowed a longest operation period of 16 days with a total of 49 hours of fogwater collection. Using information on the temperature and discharge dependence of batteries (http://pvcdrom.pveducation.org/BATTERY/charlead.htm) we estimated that at the ambient temperature we ran our MiniCASCC the battery capacity was already 5–20% below C20 and would further decrease by 6–8% if temperatures were around freezing. But since the power draw was considerably below C20 specifications, the additional capacity available for smaller currents basically compensated for the deterioration of battery performance at lower temperatures.

[Table 2 about here.]

2.4. Instrumentation

Air temperature and relative humidity were measured using Rotronic Hygroclip S3 and Rotronic MP103A sensors (Rotronic AG, Switzerland), wind speed and wind direction were measured with a Young W-Monitor (R. M. Young Company, Michigan, USA). Visibility was measured with a MiniOFS Mk II sensor (Sten Löfving, Optical Sensors, Göteborg, Sweden). Data storage and col-
lector control were done with Campbell CR510 and CR10X dataloggers (Campbell Scientific Ltd, UK).

The visibility sensor was mounted directly on the main mast. Preferably this sensor is directed to the North to prevent oversaturation from direct sunlight. In addition, a minimal distance of at least 10 m from obstacles in direction of sight must be observed. In mountaineous terrain, however, it is very difficult to place such a sensor on a south slope and still comply with these requirements. In dense fog conditions direct sunlight is absent and therefore we expect the problem of exposition to direct sunlight on the visibility to be of less concern than the distance to obstacles. Since the rain protection shield must not reach inside an angle of 45° from the beam direction, obviously a convenient sun protection cannot be constructed, at least not in extratropical regions.

These additional instruments are used to determine when the sampler should be collecting fogwater. Generally, sampling was switched on if the visibility dropped below 300 m (or below another predefined value within the visibility sensor range of up to 2000 m) and the relative humidity was above 90%. Above these thresholds or at air temperatures below 2 °C, collection was stopped. The temperature threshold was used to prevent fan damage from riming. Burkard et al. [2003] and Thalmann et al. [2002] used a threshold of 500 m to start fog collection. We found a value of 300 m more appropriate for our application, since at one site we encountered problems with the visibility measurements during nighttime. Using the lower limit reduced the time with dense fog by roughly 20% at those collectors with the best visibility data (Table 2).

To test the performance of the MiniOFS Mk II visibility sensor for our application, we compared one such sensor with a standard Vaisala PWD-11 (Vaisala Oy, Helsinki, Finland) visibility sensor at the Lägeren research site [Joos and Baltensperger, 1991; Burkard et al., 2003] during the period from 03 June 2005 to 25 October 2005. While the MiniOFS works with a backscattering principle, the PWD-11 is a forward-scattering sensor. The MiniOFS was sampled every 10 s, whereas the PWD-11 automatically produced 1 min means. Averaged data showed reasonable agreement between the PWD-11 and the MiniOFS if averaged over 10 min or more ($r^2 = 0.81$, $n = 2194$; Figure 3). Because the MiniOFS overestimates visibilities below 1000 m, a solution had to be found for minimizing the number of cases where the occurrence of dense fog with low visibility (using thresholds of 500 m and 300 m) was not indicated correctly. We parameterized a
linear model with a cutoff value of 1075 m: $VV_{PWD-11} = (0.624 \pm 0.006) \cdot VV_{MiniOFS} - (44.9 \pm 3.9)$ ($r^2 = 0.81$, $n = 2194$), where $VV$ denotes the measured visibility in meters. Fog with PWD-11 visibilities below 500 m occurred during 8.9% of the measurement period. After the transformation, the MiniOFS matched 95.8% of the time with dense fog correctly, which is a clear improvement over the 81.0% agreement before transformation. For fog with visibilities below 300 m (8.0% occurrence), the corresponding matching rate amounts to 91.7% (uncorrected 65.6%).

2.5. Performance of $\delta^2$H and $\delta^{18}$O Measurements

In addition to standard inorganic chemistry in fogwater we were also interested in analysing the ratio of stable isotopes in fogwater. These allow to characterize the provenience and history of the water source in a specific fog event (e.g. Spiegel et al. 2012a,b; Scholl et al. 2011, 2007). Stable isotopes in fogwater have gained interest in the past years, and it is not unlikely that further developments will also allow to determine the ratio of stable isotopes in the inorganic and organic components in fogwater in the near future. To assess the uncertainty of isotopic ratios measured in fogwater collected with the MiniCASCC we investigated the the isotope fractionation effect during sampling, e.g. by evaporation of fogwater from the teflon strings.

Aqueous samples were analysed for $\delta^{18}$O and $\delta^2$H values using the high-temperature carbon reduction method by coupling an elemental analyser (TC/EA; Finnigan MAT, Bremen, D) to a Delta$^{\text{plus}}$XP isotope ratio mass spectrometer via a ConFlo III interface (both Finnigan MAT; Werner et al. 1999). The TC/EA was equipped with a Nafion-trap followed by a 4-port valve [Brooks et al., 2003; Werner, 2003] between carbon reduction tube and GC column. The set-up of the reduction tube with “reversed He-flow” follows the “MPI-BGC method” described by Gehre et al. [2004]. The positioning of samples and laboratory standards (Identical-Treatment principle) in a measurement series for each $\delta^{18}$O and $\delta^2$H value measurement follows in principle the referencing procedure described by Werner and Brand [2001]. Post-run off-line calculations like offset-, memory effect-, and drift corrections for assigning the final $\delta^{18}$O and $\delta^2$H values on the V-SMOW/SLAP scale were performed according to Werner and Brand [2001]. All isotope results were normalized to V-SMOW/SLAP [Coplen, 1988]. The precision of the measurement of sample and standard water samples normally was $< 1.5\%e$ ($\delta^2$H) and $< 0.15\%e$ ($\delta^{18}$O) over all
measurements.

[Figure 3 about here.]

3. Field Tests

3.1. Collector Operation

From 7 November 2005 to 9 May 2008 one MiniCASCC was operated at the Lägeren research tower in Switzerland (47°28′42.0″ N, 08°21′51.8″ E, 682 m a.s.l.) at 35 m above ground, which is 5 m above the forest canopy. This site has already been used for fog studies by Joos and Baltensperger [1991] (winter 1986/87) and Burkard et al. [2003] (winter 2001/02), and is part of the Swiss air quality monitoring network (NABEL, since 1986). The vegetation cover consists of mixed forests (Fagus sylvatica (L.) and Picea abies (L.) Karst.). The tower is located on the southern slope of the Lägeren mountain (866 m a.s.l.) which is the southern most ridge of the Jura mountain range and marks the northern boundary of the Swiss Plateau.

From 4 April 2007 to 9 May 2008 a second MiniCASCC was installed at the same location, but at 16 m above ground level, inside the forest canopy. At this test site, it was possible to connect both collectors to mains power using a battery charger which simplified maintenance.

From 22 June to 6 October 2006 and from 23 April to 22 October 2007 (one device running until 23 November 2007) two MiniCASCC were operated on the slope of the Niesen Mountain (2362 m a.s.l.) in the Swiss Alps. One device was installed on an avalanche protection structure at 1680 m a.s.l. (46°38′32.3″ N, 7°40′03.3″ E) in a wood glade (coniferous forest) on a south-east facing slope; the second device was installed at 2330 m a.s.l. (46°38′41.7″ N, 7°39′05.8″ E; in May 2007 moved 130 m in direction North-east to 2300 m a.s.l.) on a south facing slope just below the mountain summit (alpine grassland and rocks). From 8 August 2007 to 23 November 2007 a third MiniCASCC was installed near the mountain summit (2300 m a.s.l.). These devices were supported by batteries that were exchanged during the weekly maintenance visits.

In most cases it was possible to gain weekly sample sizes > 30 mL from all devices. Best performance was found where the visibility sensor could be mounted according to manufacturer’s specifications towards north with no obstacles within 10–20 m from the sensor. This requirement
was fulfilled at the Lägeren site where also a direct comparison with PWD-11 readings was possible. However, at the Niesen site the steep topography did not allow to mount the visibility sensor in the same way. This led to artifacts in visibility readings that were clearly seen in the diurnal cycle: low visibilities during nighttime often disagreed with observed meteorological visibility. To cope with the problem we reduced the visibility threshold to power on the MiniCASCC from 500 m to 300 m, which minimized the cases of active collection under absence of fog. If fog actually was present, it was correctly detected by the visibility sensor, so the problem primarily affected the power consumption of the MiniCASCC and hence the time span it could operate without the need to replace batteries.

3.2. Airflow Measurements

Airflow measurements were performed using a TSI Velocicalc 9660 hot-wire anemometer (TSI GmbH, Aachen, Germany; probe type 964 with integrated temperature and pressure sensors) in the inlet area (10 cm in front of the strands) and inside the tube between the strands and the flow laminator. For each measurement point the mean flow velocity was averaged over 60 seconds, using 1 s measurement intervals. These measurements, carried out in a sampling matrix of 11×11, required one full day under laboratory conditions. The precision of the instrument is 5% of the final value, or ±0.005 m s⁻¹ at low speeds.

The measured flow velocities (Figure 4) show some spatial variation but are close to what could be expected from the technical information that indicate a flow of 2.55 m³ min⁻¹ at full load, which translates to an air speed of 4.25 m s⁻¹ inside the 10×10 cm² cross-sectional area of the MiniCASCC where the strings are located. The inlet side is ≈ 20% larger than the strand area, resulting in lower mean air speed: an average of 3.62 m s⁻¹ was measured in a 11×11 sampling matrix in the inlet area (at a distance from the strings) and 4.32 m s⁻¹ immediately behind the string area (air pressure 974 hPa at time of measurement). The latter is the best estimate for the air speed needed to compute the collection efficiency at the strings. For a 6×6 matrix the corresponding values were 3.63 respectively 4.26 m s⁻¹. The differences are well within the ±5% range specified
by the manufacturer, and hence we only measured 6×6 matrices in subsequent assessments of the airflow rate in the field, which could then be performed within 2 hours. Under ambient conditions at the Niesen Kulm site (2300 m a.s.l., air pressure 778 hPa at time of measurement) the mean inlet air speed was only 3.50 m s$^{-1}$. This implies an air speed of 4.10 m s$^{-1}$ in the tube if a linear increase is assumed between inlet and tube. Even though the air speed is a factor 2 lower than indicated by the manufacturer, the air speed is still above the critical value of 2 m s$^{-1}$, below which a significant size fractionation of the droplet spectrum would occur. At the measured air speed the droplet cutoff diameter is ≈ 6 µm. If air speed can be increased to 5.0 m s$^{-1}$ the cutoff diameter drops to 5.0 µm, whereas a drop of air speed to 3.0 m s$^{-1}$ would increase the cutoff diameter to 6.5 µm.

3.3. Collection Rates and Efficiencies

The collection rates from all field deployments are shown in Figure 5. Overall, the median collection rates (bold horizontal bars in Figure 5) are between 12 and 30 mL h$^{-1}$. The very low values can be explained by malfunctioning of the visibility sensor (erroneous indication of low visibilities, see Section 2.4). The highest collection rates were observed at the Niesen and reached up to 40 mL h$^{-1}$ during fog periods. In almost all cases it was possible to gain the required sample size of 30 mL for a weekly sample.

To get a more precise assessment of the collection efficiency, especially for clouds with low LWC, it is possible to calculate theoretical droplet distributions and derive the overall collection efficiency for a given LWC value. Typical droplet distributions rise from a low value to a maximum, and then decrease slowly toward larger sizes [Pruppacher and Klett, 2010]. For the assumption of theoretical droplet distributions we used the same approach as Demoz et al. [1996], who used parameterizations presented by Best [1951]. They expressed the volume fraction of droplets with a diameter between $d_p$ and $d_p + \Delta d_p$ (in µm) as

$$\beta(d_p) = \left(\frac{n}{a}\right)\left(\frac{d_p}{a}\right)^{n-1} \exp\left(-\left(\frac{d_p}{a}\right)^n\right),$$  (4)
with parameters \( n = 3.27 \) and \( a = (909.1 \cdot \text{LWC})^{0.559} \), where LWC is expressed in g m\(^{-3}\). With higher LWC the mean droplet diameter increases, and is 8, 11, and 16 µm for LWC values of 50, 100, and 200 mg m\(^{-3}\), respectively. As the cutoff value of the MiniCASCC is around 6 µm, the corresponding volume amounts which are above this cutoff value are 78, 93, and 98% of the total LWC, respectively. Therefore, the overall collection efficiency of the MiniCASCC increases since the volume fraction of small droplets decreases (Figure 6). The highest percentage of fog droplets above the threshold reaches 98% and is typical for radiation fog events, the most common type of fog in mountain valleys. At an air speed of 4.2 m s\(^{-1}\) and a LWC of 20 mg m\(^{-3}\) the total collection efficiency amounts to 0.27. At LWC values of 50, 100, and 200 g m\(^{-3}\) the corresponding collection efficiencies are 0.54, 0.68, and 0.76. For LWC values of 300 mg m\(^{-3}\) and higher (thick fog with low visibility), the collection efficiency increases towards 0.81. As a consequence, the assumption of a constant collection rate of 0.81 overestimates the effective sampling rate in the fog by a factor of 2.9 at an LWC of 20 mg m\(^{-3}\) and by a factor of 1.2 at 100 mg m\(^{-3}\) (Figure 6). An uncertainty of ±10% (±25%) in the air speed leads to an uncertainty of ±6% to ±1% (±15% to ±2%) in efficiency estimates at LWC values ranging from 40 to 200 mg m\(^{-3}\). This indicates that LWC estimates derived from MiniCASCC collection volumes are robust against uncertainties in air speed in the collector tube. Hence the assumptions made for droplet size spectra are of greater concern. The theoretical droplet size spectra by Best [1951] have the tendency to predict larger amounts of small droplets for a given LWC as compared to what field measurements by Burkard et al. [2002] presented, but fit the measured droplet spectra quite well if the LWC is treated as a free fitting parameter for \( a \) in Eq. (4), except that the amount of large droplets is underestimated. LWC computed from collection rates obtained from the MiniCASCC thus remains uncertain to the degree that the true distribution of droplet sizes remains unknown without specific additional measurements. In a given fog at a given site the uncertainty in collection efficiency (\( \eta \)) and LWC (mg m\(^{-3}\)) are inversely related to each other via the collected volume \( V_c \) (mL),

\[
\text{LWC} = \frac{\rho_{\text{H}_2\text{O}} V_c}{\eta},
\]

with \( \rho_{\text{H}_2\text{O}} \) the density of water (1000 g L\(^{-1}\)). As mentioned in Section 3.3, the Best [1951] approach allows the computation of the efficiency in capturing small droplets, but the loss of large droplets
is not adequately covered by this approach. We hence repeated our efficiency calculations with two measured droplet spectra by Burkard et al. [2002] to avoid using the estimates derived via
Eq. (4). For a fog with a relatively low LWC of 40 mg m$^{-3}$ and the peak of the distribution between 10 and 15 µm we derived a collection efficiency of 0.71 and for a LWC of 205 mg m$^{-3}$ the collection efficiency was 0.79, whereas the modelled rates would amount to 0.49 and 0.76. These are deviations of +45% and +4% from theory, which translate to slight overestimations of LWC by 32% and 4% for low and moderate LWCs, respectively. Thus, if LWC estimates from the MiniCASCC underestimate true LWC, then this is most likely associated with the unknown losses of large droplets and is not directly related to the theoretical estimate of the collection efficiency of the smallest droplets, for which the critical cutoff diameter is specified.

So far the potential losses of large droplets (e.g. due to wall effects in the sampling device or flow conditions at the inlet) has not been considered in efficiency calculations, but may be of relevance: Wieprecht et al. [2005], for example, found that the collected volumes were generally lower than predicted collection rates. The difference was rather small at low LWC but increased with LWC and share of large droplets in the droplet size spectrum. For the set of fogwater collectors they inspected they determined an overall collection efficiency of 45–79% of the theoretically expected one. An even lower value of 27% results for an example from Puerto Rico [Eugster et al., 2006] where fog collector derived LWC had to be enlarged by a factor 3.75 to match values obtained with an FM-100 fog droplet spectrometer (Droplet Measurement Technologies, Inc., Boulder, CO, USA). It is therefore advisable for future methodical studies to add an additional verification step, in which the collected water amounts are compared against concurrently measured LWC and during different wind speed conditions at different sampling intervals.

[Figure 6 about here.]

3.4. Stable Isotope Sampling

Evaporation of water from droplets collected on the strings tends to increase the remaining concentrations of chemical solutes in the water sample. The same process is known to affect the ratios of stable isotopes $^2$H/$^1$H and $^{18}$O/$^{16}$O (termed isotope fractionation). This however would be indicative of a sampling artefact of the device, because theoretical considerations made by Spiegel
et al. [2012a] have clearly shown that in undisturbed clouds such isotope fractionations should not occur.

In order to test if the MiniCASCC is sampling fog water without isotope fractionation we sprayed water samples of deionized water in the inlet and collected the resulting water samples. The spray was generated with a plant sprayer which works with pressurized air. It can be expected that the drops are somewhat larger than in typical fog, since gravitational settling can be observed for the largest part of the sprayed water. These sprayings were repeated several times in the laboratory and also in the field at the Niesen Kulm site. Since fog occurs under saturated conditions and our measurements were performed under fog free conditions (i.e., unsaturated air—both in the laboratory and at the Niesen Kulm site) to prevent contamination with fog droplets, the experimental setup did not perfectly fulfill realistic, but rather worst-case conditions. The \( \delta^2 \)H and the \( \delta^{18} \)O values of the test water samples were measured before and after sampling. Our analysis indicates a shift of +0.69‰ for \( \delta^{18} \)O (\( \sigma=0.23 \), \( n=3 \)), and +2.63‰ for \( \delta^2 \)H (\( \sigma=0.84 \), \( n=2 \)) under laboratory conditions (20 °C, relative humidity of 60%). Under field conditions at the Niesen Kulm site four parallel measurements of the samplers (K) and (B) with sufficient amounts of water were available. Two pairs of samples had to be rejected (damaged vial and disrupted measurements). The remaining two samples showed differences of −0.19 and −0.28‰ for \( \delta^{18} \)O, respective −1.75 and −0.95‰ for \( \delta^2 \)H, which is almost within the measurement accuracy of 0.15‰ (\( \delta^{18} \)O), respective 1.5‰ (\( \delta^2 \)H) of the isotope ratio mass spectrometer and hence cannot be considered significantly different from zero, as expected by Spiegel et al. [2012a]. We were unable to test whether under real fog conditions with a relative humidity around 100% it would be possible to come closer to a zero difference. Our results however show that the MiniCASCC does not introduce an unacceptable bias for stable isotope ratio measurements in fogwater.

4. Discussion

While the basic principles of CASCC collectors are well known and documented (e.g., Daube et al. 1987, Demoz et al. 1996), our modification extends the operation range of these collector types to more remote sites where no access to mains power is possible. Due to the relatively low cost of one single fog collector—ca. € 800 for material and batteries (without labor) plus € 2,500
for sensors and data acquisition—, we were able to produce multiple devices and compare them at different locations. During the two field seasons (1597 days of operation in total) we could gain good insights into collector operation under different environmental (Jura Mountains and Alps) and seasonal conditions (spring, summer, fall).

The absence of concurrently measured droplet size spectra and direct measurements of liquid water contents limited our ability to perform a quantitative assessment of the presented calculations in Figures 1 and 6. Nevertheless, available data from previous studies at the Lägeren site [Bützberger, 2002] report LWC in the same range as what could be deduced from our measurements of collection rate. Although LWC estimations are robust against uncertainties in air speed estimates (Section 3.3), the quality of LWC estimations obtained via MiniCASCC could be further improved by measurement of the effective air speed in the collector tube. Air speed depends on the external wind speed, therefore we assume that the effective air flow is higher when the wind blows towards the collector front, whereas lower air speeds would result with opposite wind direction.

With the triangular rain hoods on both the inlet and the outlet sides (see Figure 2) the effect of the external wind speed on air speed inside the device should however be relatively small. Moreover, during dense fog events, wind speeds were generally below 0.8 m s$^{-1}$ at Niesen Schwandegg (S) and Lägeren (L, 35 m a.g.l.), and below 2.7 m s$^{-1}$ (0.75 quantile) at Niesen Kulm and Lägeren (X, 16 m a.g.l.). Thus, we do not expect large deviations in the collection efficiency (and hence derived LWC) during field operation from those determined under laboratory conditions via the measured air speeds within the collector tube (Figure 4). The air speed in the device is well below 20 m s$^{-1}$ where Moore et al. [2002] found that larger drops can deform or break up in smaller droplets. Thus, there is no concern for this to happen in the MiniCASCC.

For the aspect of concentrations of inorganic ions or ratios of stable isotopes in fogwater the overall uncertainty in efficiency or LWC is not of critical importance. In the case of chemical compounds it is primarily of interest where the cutoff diameter lies, since concentrations are typically higher in smaller than in larger droplets. Accurate LWC and sampling efficiency estimates are however crucial for determining total fluxes of chemical solutes. This is also hampered by the challenge to make a sound decision when to turn on the MiniCASCC and when to keep it powered off to conserve energy. Using a low-cost visibility sensor did not convincingly allow us
to get the best possible performance at the south exposed slope of the Niesen Mountain. Here the
visibility sensors had to be directed east to south due to topographical restrictions. This resulted
in an apparent diurnal cycle of visibility during non-fog conditions due to light oversaturation of
the sensor during daytime (obviously due to direct sunlight). During conditions with cloud tops of
roughly 50–150 m above the collector (position of the sun can be seen) oversaturation of the sensor
occurred as well. This effect cannot be avoided by shielding the visibility sensor since reflections
can occur from all sides, and hence would require a different operation principle for the visibility
sensor. External light sources at night might also have led to erroneous signals. Since the sensor
works on a backscattering principle at 850 nm wavelength (output $< 5$ mW), the data quality is
lower than that obtained with a forward-scattering instrument like the PWD-11 due to physical
limitations of the measurement principle [WMO, 2008]. A newer low-cost sensor developed and
tested by Carrillo et al. [2008] most likely should be able to avoid such problems in future studies.
Power consumption should not be the main issue since such a sensor could also be operated in
pulsed mode to conserve battery power, but under rainy and snowy conditions this sensor tends to
fail, and a reliable alternative of a low-cost visibility sensor yet needs to be developed.

5. Conclusions

We developed the MiniCASCC, a modified Caltech active strand cloud water collector for
operation in areas without access to mains electricity. After two extended summer seasons we
deployed three (2006) to five (2007) MiniCASCC devices at three different sites, to test their
suitability for biogeochemical field research that aims to collect integrated samples to determine
ion loadings or stable isotopes in cloud water over extended periods. In most cases the collection
efficiency was high enough to obtain sample amounts of $\approx 30$ mL from a single fog event of $\geq 5$ h
with an average LWC of $50$ mg m$^{-3}$, which is sufficient for the examination of basic inorganic
chemistry and isotopic composition of the collected cloud water, its pH and conductivity.

The weakest part of our device remains the fog detection using low-cost visibility sensors.
These sensors are very sensitive to light oversaturation and reflections which compromised the
overall fog collection performance. Future studies should therefore put more emphasis on the op-
timization of fog detection as this is the key variable to obtain representative and reliable collection
of fog water in field experiments. On the other hand, the collection process with a MiniCASCC at a horizontal visibility < 300 m was excellent and clearly meets the requirements for chemical analysis of major ions and stable isotopes in fog water.

Acknowledgements

This research project was funded by the Institute of Geography of the University of Bern. We thank Prof. Dr. H. Wanner for his generous support of the project in many ways, and the mechanical workshop staff of the Department of Chemistry for the technical realization of the MiniCASCC. The Niesenbahn AG, Switzerland, the Armed Forces Command Support Organisation (FUB), and the Empa (Swiss Federal Laboratories for Materials Testing and Research) are acknowledged for their logistic support at the different sites. We thank the two anonymous reviewers for their very careful and detailed assessments which strongly helped to improved this paper.

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Vitae of the Authors

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Pavel Michna recently obtained a PhD degree at the Geographical Institute of the University of Bern. His research interests are the development of measurement devices for fog/cloudwater collection for biogeochemical research, fog- and cloudwater chemistry, development of software for meteorological and climatological applications, and micrometeorology. He has obtained a MSc degree in Geography at the University of Bern, where he has been working on the validation of tropospheric ozone models on the continental scale.

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Roland A. Werner is an expert for technical aspects of isotope ratio measurements and a scientist at the ETH Zurich, Switzerland. His main research interests are the correlation and explanation of inter- and intramolecular isotope distributions in natural plant compounds based on biosynthesis and metabolism and the theoretical background of isotope fractionations in plants. He received his PhD degree from the Technical University of Munich, Germany, and has worked as a Deputy Lab Manager at the Max-Planck-Institute for Biogeochemistry in Jena, Germany.

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[Figure 7 about here.]
Figure 1: Total efficiency curves for different configurations of the MiniCASCC with 6 rows of strings. Default values are: inclination angle of strands from the vertical $\theta = 35^\circ$; air viscosity $\mu = 1.717 \cdot 10^{-5} \text{ N m}^{-2}$; density of water in droplets $\rho = 1.0 \cdot 10^3 \text{ kg m}^{-3}$; strand diameter $d_c = 0.5 \text{ mm}$; strand spacing $d_s = 2.0 \text{ mm}$; air speed $U = 8.0 \text{ m s}^{-1}$. The bold line shows the efficiency of the CASCC2 as indicated in Demoz et al. [1996].
Figure 2: Complete view of the MiniCASCC, mounted at the Niesen Kulm site (2330 m a.s.l.). Above the panel box the boom with the anemometer and the thermo-/hygrometer, and the collecting unit are seen, plus the lightning protection rod.
Figure 3: Comparison between the MiniOFS Mk II and a Vaisala PWD-11 visibility sensor (10 min averages).
Figure 4: Air flow velocity measured under laboratory conditions. The left panel shows the inlet flow field, the right panel the tube flow field behind the string area. Black dots indicate the points of measurement (mean of 60 values).
Figure 5: Box plots of collection rates during the field seasons 2006 and 2007. Collectors K and B were located at Niesen Kulm, S at Niesen Schwanegg, L and X at Lägeren. B and X were only installed during the 2007 field season.
Figure 6: MiniCASCC collection efficiency (left) and collection rates (right) as function of liquid water content (LWC). The greyshaded areas represent the ±10% range around the nominal air speed of 4.2 m s\(^{-1}\). Eff\(_1\) shows the theoretical upper limit of an efficiency of 1.0, Eff\(_{0.8}\) denotes a constant collection efficiency of 0.8 and Eff\(_{MOD}\) a collection efficiency which depends on LWC as shown in the left panel, using modelled droplet spectra. Droplet spectra were calculated with the same approach as in Demoz et al. [1996] using the theoretical droplet size spectra according to Best [1951].
Figure 7: Authors. From upper left to lower right: Pavel Michna, Jürg Schenk, Roland A. Werner, and Werner Eugster.
Table 1: Characteristic dimensions and operating parameters of the CASCC, CASCC2 (both from Demoz et al. 1996), and the MiniCASCC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CASCC</th>
<th>CASCC2</th>
<th>MiniCASCC</th>
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<tr>
<td>Collector dimensions (inlet) [cm]</td>
<td>23 × 23</td>
<td>11 × 11</td>
<td>10 × 10</td>
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<td>Strand diameter [mm]</td>
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<td>0.508</td>
<td>0.5</td>
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<tr>
<td>Strand spacing [mm]</td>
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<td>1.8</td>
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<tr>
<td>Number of rows</td>
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<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Air speed [m s⁻¹]</td>
<td>8.5</td>
<td>8.6</td>
<td>4.2</td>
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<tr>
<td>Flow rate [m³ h⁻¹]</td>
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<td>348</td>
<td>151</td>
</tr>
<tr>
<td>Size cut [µm]</td>
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<td>3.5</td>
<td>5.5</td>
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Table 2: Occurrence of fog sampling periods according to different definitions during the field seasons 2006 and 2007. General thresholds were 2 °C for air temperature and 90% for relative humidity. Specific visibility thresholds were changed from 500 m (column Fog$_{500}$) to 300 m (column Fog$_{300}$) during field sampling (see Section 3.1). The percentage of hours classified as fog with a visibility threshold of 300 m compared to 500 m is given in column Fog$_{300}$/Fog$_{500}$, and $n_{OBS}$ denotes the total number of observations.

<table>
<thead>
<tr>
<th>Collector</th>
<th>Fog$_{500}$ [%]</th>
<th>Fog$_{300}$ [%]</th>
<th>Fog$<em>{300}$/Fog$</em>{500}$ [%]</th>
<th>$n_{OBS}$</th>
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<tr>
<td>Niesen Kulm (K)</td>
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<td>Niesen Kulm (B)</td>
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<td>Niesen Schwandegg (S)</td>
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<td>Lägeren (L)</td>
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<td>3.6</td>
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<td>Lägeren (X)</td>
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<td>71,107</td>
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