Response to comments of Referee #1

We would like to thank Referee #1 for his valuable and thoughtful comments, which helped us a lot to improve the content and quality of our manuscript. In the following we have addressed all the comments of the Referee and incorporated changes in the manuscript as follows:

Blue: Comments of Referee #1

Black: Answers of Authors

Black, italic, “”:“Changes in the manuscript”

RC1: Anonymous Referee #1

1.1 UAV should be replaced with UAS (unmanned aircraft system) throughout.

Actually the terms UAV and UAS are not used uniformly in literature; in particular, both terms are still common at present. Even in the key references kindly recommended by Referee #1, very similar aerial measurement systems are referred to as both "unmanned aerial vehicle (UAV)" (Schmale, 2010) as well as "unmanned aircraft system (UAS)" (Schmale, 2015).

In order to avoid conceptual ambiguities, we carefully use the terms UAV and UAS in different ways uniformly throughout the text: the term unmanned aerial vehicle (UAV) is used to describe the aircraft (as the aerial vehicle) itself, whereas the term unmanned aerial system (UAS) is used to describe the entire operation system, including the unmanned aerial vehicle, the payload with measuring equipment and further accessories to control the system from ground.

1.2 Multicopter should be replaced with rotary-wing UAS or hexacopter (the S900 is a hexacopter platform).

We deliberately choose the term “multicopter” because this term seems to us to be very accessible and is currently very common in the more recent relevant literature (e.g. the cited Brosy, 2017). The use of the term "rotary-wing" might be misleading with regard to the aerial vehicle actually applied during our work, since "rotary-wing" is – according to our understanding – also used as a generic term for helicopters.

On the other hand, the term "hexacopter" seems to be too narrow, since the number of propellers (e.g. four, six or eight) is of no relevance for the presented subject-matter.

With all due respect for the well-intentioned commentary, we would therefore prefer to keep the terms we have chosen.

1.3 Moreover, the platform itself is not new. It is the collection system being used on the UAS that is new and interesting. This needs to be re-shaped in the text.

We fully agree with your focusing on the particle collection system (PCS) as the new and interesting aspect. In order to further clarify this, we amended the abstract and the introduction by emphasizing that the PCS is "newly in-house developed" whereas the multicopter UAV is "commercially available" as already stated in the originally filed text on chapter 2.1., first line:

Abstract: "The application of a newly in-house developed particle collection system (PCS) onboard a commercially available multicopter unmanned aerial vehicle (UAV) is presented as a new unmanned aerial system (UAS) approach for in-situ measurement of the concentration of aerosol particles such as pollen grains and spores in the atmospheric boundary layer (ABL)."

Introduction: "In this paper we present the structural design and first application of a newly in-house developed particle collection system (PCS) operated onboard a commercially available multicopter UAV (Fig. 1) for in situ measurement of the concentration of pollen and spores in the ABL"

2. The introduction and results and conclusions are missing some key references regarding the sampling of the lower atmosphere with UAS.

Many thanks for the literature recommendations, emphasising especially the relevance of the topic in agriculture science.

As can be seen from the attachment no. 1, all references recommended by referee #1 have been introduced in the sections introduction or conclusions, and further have been added to the list of references (added references are highlighted).

3. Details on the operation of the sampling device are limited. Was the device powered on remotely once the UAS had reached the desired altitude? Or was it sampling on its way up and down from the target sampling altitude? Is this why you conducted the profile missions? If not, why didn't include a remote switch to power a unit? In fact, you can use a light activated trigger sensor and turn the LEDs on and off from a DJI platform to act as a switch for this using the DJI platform and software.

Yes, the newly developed particle collection system (PCS), namely its electrically operated blower, was powered on remotely once the UAS had reached the desired sampling altitude. We tried to make this clear e.g. with the last sentence in section 2.2.4 (page 10, line15: "One channel of the remote control system was used to switch the blower on and off when the multicopter UAV was airborne and the particle collection position was reached.") or with the second sentence of the second paragraph of chapter 3.4 (page 16, line 31: "Table 1 gives an overview of these aerosol particle collection flights including data concerning the altitude above ground level at which the particle collection system was activated,…").

Technical details concerning the remote operation of the blower are deliberately limited, because we had considered them to be too simple to mention and seemed superfluous to us in this context.

Nevertheless we apologize for any remaining ambiguities. To describe the procedure for particle collection even more clearly, we amended the text at the end of chapter 2.2.4 by adding the following to the text:

"As long as the blower was switched on, i.e. as long as particle collection was performed, the multicopter UAV was maintained (by hovering) in this desired particle collection position. Before leaving this position, the blower was remotely switched off, thus terminating the particle collection operation. The value of the electrical current, drawn by the blower from the battery, was measured onboard the multicopter UAV and transmitted to and monitored on ground, to make sure that the blower has really went into operation (switched on) or was really out of operation (switched off)."

Furthermore we have amended the following wording (underlined) in second paragraph of section 3.4:

"*Table 1 gives an overview of these aerosol particle collection flights including data concerning the <u>hovering</u> altitude above ground level, at which the <u>blower of the</u> particle collection system was activated, the airborne particle collection start time, as well as the measured air temperature, wind direction, and wind speed on ground. On March 3, 2017, the <u>blower of the</u> PCS was activated during <u>hovering</u> in 25 m, 100 m, and 200 m altitude a.g.l. and also – as an additional measurement – on ground with the propellers of the multicopter UAV being not in operation. On March 10 and 16, 2017, the PCS was activated during flights in 25 m, 200 m, and 300 m altitude a.g.l.. The particle collection <u>duration</u> at each altitude was 10 minutes, with a sampled air* *volume of 2,000 standard litres, corresponding to 2 m^3 under standard conditions, which are 20°C and 1,013.25 hPa according to the data sheet of the mass flow sensor."*

4. What precautions were taken to clean the inlet and the inlet pipe in between sampling missions?

Various precautions have been taken in the laboratory as well as in the field. In view of your esteemed comment, we have added the following new paragraphs 3 and 4 in section 3.4 to describe our precautions even better:

"*Prior to each day of aerosol particle collection flights, the bellmouth-shaped air inlet, the tube leading to the impactor, the O ring and the two housing halves were cleaned in an ultrasonic bath with soapy water for 15 min, then rinsed with deionized, filtered water (0.3 µm Membrane Filter) and dried in a particle-free environment (laminar air flow box, HEPA H14 filter). Once the parts were dried, the impactor was assembled (excluding sample carrier) and packed together with the inlet into a new, clean, sealable storage bag."*

"In the field again, shortly before the particle collection operation, the impactor was taken out of the sealed storage bag, the sample carrier was installed in the impactor and the inlet was plugged onto the tube leading to the impactor. In-between the sampling flights shortly before the next flight operation and shortly before installation of the next unloaded sample carrier, the impactor and the bellmouth-shaped inlet were flushed with filtered air using an battery operated electric blower with a medical ventilation filter installed on its inlet (type Pall Ultipor 100, > 99.999 % retention of airborne bacteria and viruses)."

Experiments which tested the surface of the bellmouth-shaped inlet with a sticky film have shown that no significant particle numbers were deposited on the inner wall of the inlet and downstream tube, even in case of high particle load in the atmosphere.

5. In general, the figure legends do not contain enough information for the figure to stand alone without referencing back to the text. Figure 5 is a great example of this.

We apologize for initially insufficient figure legends and have amended these to provide all necessary information, as can be seen from attachment no. 2.

6.1 What sort of quantitative data were measured for experiments described in Figure 6 ? There appear to be only qualitative observations. Could you use image-processing tools like IMageJ to formally track the plume of smoke?

The experiments shown in Figure 6 were conducted to evaluate the best position for the air intake of the particle collection system with regard to isokinetic sampling conditions. As described in section 4.1, the velocity of the air above the copter was calculated by visually tracking characteristic parts of the smoke plume and determining their propagation in consecutive frames (every 40 milliseconds) of the video recording. The results of these experiments are in very good agreement with the computational fluid dynamics (CFD) calculations reported by reference Haas et al. (2014). Nevertheless, as already mentioned in the text at the end of the third paragraph of section 4.1, "…, a more precise determination of the vertical acceleration and velocity of the air flow above the multicopter UAV would be a valuable aspect of future work on this subject.".

6.2 Did you trap any of the smoke particles on your collection device?

Answer: No particle collection operation was performed during the smoke experiment. In another experiment performed in the laboratory, the separation ability of the impactor was tested with smoke particles. As a result, a coloured particle deposit was detected on the sample carrier, but not (yet) evaluated. It can be assumed that the smoke particles of the pyrotechnic smoke are very small (approx. 0.1-1 µm). The question whether the newly developed particle collection system is able to separate smoke particles is very interesting, but was not subject of this publication.

7.1 Your particle trapping efficiency experiments based on two inline trapping surfaces and a single experiment are just not enough. You should aerosolize known particle sizes (such as flourescent microspheres that you can buy at set size ranges), and attempt to trap them on your sampling device. Your efficiency will likely be linked to the size of your particle.

We really appreciate the encouragement to do more research into the separation efficiency of our impactor.

We are aware that we cannot exclude the possibility that certain particles, whether due to their size and/or due to their morphology, may not be captured by the newly developed particle collection system. And we fully agree that the efficiency depends on the size of the particles. However, as already stated in the title, the present publication is about the collection of "pollen and spores". And in this respect, the results indicate that, in any case the actually collected pollen and spores were trapped with very high efficiency. Originally, we had expected that possibly a significant part of the impacting pollen and spores would not be retained by the sample carrier of the first impactor, but would detach again, e.g. due to the high mean jet velocity of 50 m s^{-1}. Such detached particles, re-entering the air stream, would then have had to be deposited predominantly on the cascaded second impactor, which was not the case.

Two scenarios A and B can be theoretically reflected:
scenario A: The extraction efficiency is 100 %, thus all particles would be extracted in the first impactor, none will reach the second impactor.
scenario B: The extraction efficiency is 50 %, thus 50 % of the particles would be extracted in the first impactor, and 25 % in the second impactor.
The results of the conducted extraction efficiency experiments are much closer to the scenario A than to the scenario B.

In addition to the experiment with the impactor cascade described in this publication, we have also carried out another experiment (not described in the publication) to gain more insight in the extraction efficiency of our impactor:
In this experiment we replaced the downstream impactor with a filter element trapping particles potentially passing by the first impactor stage. These experiments were carried out partly outside in the field, as long as there was enough pollen and spores in the air, and partly in the laboratory using an artificially generated aerosol employing spores of *Lycopodium*. As a result after sampling for 10 minutes, no particles could have been detected on the filter element, whereas the first impact stage was loaded with particles such as pollen grains and spores in the magnitude of about 500 to 1,000 particles.

7.2 Many of the smaller particles probably go cruising on by the initial trapping surface

The impactor used in this work is intended to separate particles such as pollen grains and spores with a high separation rate. Other, smaller particles were not of interest within this work.

In general, it can be assumed that impactors optimized for the extraction of pollen grains and spores do not automatically provide the same efficiency for particles that are significantly smaller, e.g. for nanoparticles.

It can be expected that - in order to achieve specified separation efficiency - the smaller the particles, the higher the velocity of the air jet (impaction velocity) must be. The widely used Burkard pollen and spore trap uses a mean impaction velocity of about 5 m s^{-1} to remove pollen from the air stream. For the separation of spores being of a smaller size than pollen, the company recommends a modified inlet that increases the mean flow velocity to about 25 m s^{-1}. For comparison: the mean flow velocity in our impactor is 50 m s^{-1}.

7.3 Your final inline sampler could be an impinger, to collect all of the material in a liquid and use that as a basis of quantification

We are considering your proposal to use an impinger for future experiments but see the problem of reliably detecting a small number of particles in the liquid.

8.1 Table 1 needs to be overhauled. Order by start time, not by altitude. Also, list stop time of collection.

Table 1 is intended to give an overview of the measurement flights. For this purpose, the order in the first column by date and in the second column by altitude still seems suitable, especially with regard to the subject of this publication, namely to demonstrate the operational capability of the new system at different flight altitudes.

As it is stated three lines above table 1, that “the particle collection time/duration at each altitude was 10 minutes,…”, the “stop time of particle collection” can be easily calculated from the “start time of particle collection” given in table 1. Thus we prefer to indicate only the start time in table 1.

8.2 Why did the authors choose different sampling times on different days? What is the justification for this? Why not sample the same altitude at multiple times throughout a single day? As it stands, you only present 3 reps of data for 25m and 200 m. 100m is not replicated, and 300 m was only flown twice.

The measurements presented in this publication primarily serve as a functional demonstration of our new measuring method. Different flight altitudes and sampling times are due to the fact that we wanted to slowly approach the limits of the system. However, all 10-minutes flights started between 2 p.m. and 4 p.m. local time with no rain, temperatures between 15 and 20°C and low wind speed on ground, i.e. comparable atmospheric conditions to be expected (convective conditions). In the future we certainly will focus more on the importance to the comparability of the measurements.

9. Delete Figure 8. This is really just meant for the discussion.

According to our opinion, figure 8 provides a very easily accessible overview of the possible influences of the different components of the newly developed particle collection system on the finally determined particle concentration, and thus supports the discussion very vividly.

10.0 Table 3 needs to be completely overhauled. Consider separate rows for each flight, and separate columns for the pollen and fungi analyzed.

We have completely revised table 3; please see attachment no. 3.

10.1 I am concerned about the fungal genera presented in this table. The authors report Puccinia and Epicoccum, but the 'fungal spores' they show in Figure 9 do not appear to be representative of either of these genera.

Something has been mixed up during manuscript preparation. The reviewer is right. We have amended the following wording (underlined) in second paragraph of section 4.4.1:

"*Only pollen of the genus Taxus, Corylus, Alnus, Cyperaceae, and Salix were counted and listed as well as two types of fungal spores. Fungal spore type 1 probably belongs to the genus Cladosporium, whereas type 2 most likely belongs to the genus Epicoccum. Furthermore, charcoal particles with a longitudinal extension of more than 20 µm were also counted. Additionally, a large number of small aerosol particles down to a size of less than 1 µm were visible under the microscope, but are not listed as they cannot be reliably identified by visual inspection only. Figure 9 shows a photograph of the sample carrier content as an example of one of the collection flights.*"

11. Figure 10 needs to be formatted for publication. I'm not sure what the authors are trying to do here, since they show these data in Table 3.

Figure 10 has now been revised for publication, as can be seen from the attachment no. 4, and is a visualization of the data of Table 3.

12. I don't understand the need for Figure 11. Why was 25 m reported? Was this the altitude the reference data were recorded at?

Figure 11 is a visualization of the comparison of the pollen concentrations of the types Corylus and Alnus measured 1. by us in Poltringen with our newly developed measuring system 25 m a.g.l. and 2. by MeteoSchweiz in Zürich using a Burkard pollen sample near ground level. Unfortunately, no data concerning the concentration of pollen type Taxus and no spore concentration values are provided by MeteoSchweiz, so we had to limit the comparison to the pollen types Corylus and Alnus.

13. Finally, no hypotheses are stated or tested. This makes it very difficult to judge the merits of this work. Did you expect to find different concentrations of pollen at different altitudes? If so, why? How might the concentrations of pollen change throughout a day or night? Did you hover at a single location? What about hovering a multiple locations, but maintaining precise altitudes? More flights are needed to really show the value of this platform. Do you know where the pollen is coming from? Just because a forest is nearby doesn't mean the pollen was coming from there...

The present work describes the development of a new impactor-based particle collection system and its use on a multicopter-based unmanned aerial vehicle. The combination of a high sampling air volume flow of 0.2 m^3 per minute and the hovering possibilities of a multicopter UAV provides the potential of particle collection with high temporal and spatial resolution.

And yes, we expected to find different concentrations of pollen at different altitudes, as for example reported by Damialis et. al., 2017, and also by the reference Lin et. al. 2014 that you recommended for citation under item 2. of your comment.

And we also expect a change in pollen concentration between day and night, at least due to the influence of the daily cycle of the atmospheric boundary layer (ABL), e.g. during the morning transition with the dissolution of the nocturnal inversion layer and the formation of a convective layer.

But all these questions were not the subject of the present work, but will be the subjects of future studies working with the newly developed equipment. In any case, the result of the present work provides a valuable tool for investigating all these interesting questions.

Attachment no. 1

1 Introduction

In-situ measurements of the concentration of aerosol particles such as pollen, spores, and fine particulate matter in the atmospheric boundary layer (ABL) are of great interest in numerous scientific disciplines (Hardin & Hardin, 2010).

For example, in agricultural science, the concentration and aerial dispersal of pollen and spores is of interest with regard to an optimization of yield (Aylor, 2005), the spread of plant diseases (Aylor et al., 2011), and also with regard to the spread of transgenic material originated from genetically manipulated corn (Hofmann et al., 2013). In particular, plant pathogens are able to travel hundreds or even thousands of kilometres through the atmosphere from their origin to the place where they cause damage (Schmale & Ross, 2015). The travel distance but also concentration of pollen is furthermore dependent on the seasonal atmospheric convective conditions (Boehm et al., 2008). For example, seasonal variations have been reported for fungal spores of the genus *Fusarium* (Lin et al., 2014) with distributions in altitudes of 40 to 320 meter above ground level (m a.g.l.) as reported by Schmale et al. (2012) using an unmanned aerial vehicle.

In meteorology, it is known that mineral dust particles originated from Saharan dust storms and transported for example to Southern Florida effectively act as ice nuclei being capable for glaciating super cooled altocumulus clouds (Sassen et al., 2003). Also spores of which millions of tons are dispersed into the atmosphere every year, may act as nuclei for condensation of water in clouds (Hassett et al., 2015). It is also suggested, that some atmospheric microbes could catalyse the freezing of water at higher temperatures and may facilitate the onset of precipitation (Jimenez-Sanchez et al., 2018). Thus, the knowledge about the spatial distribution and transportation distances of dust particles, pollen, spores, and microbes would allow the determination of their contribution in cloud formation processes, which are influencing not only local weather, but also regional or even worldwide our climate. Meteorological processes have a great influence on the propagation behaviour of the aerosol particles in the ABL. For in situ measurements of relevant meteorological parameters in the ABL, e.g. the air temperature with high temporal resolution, a remotely piloted fixed-wing unmanned aerial vehicle (UAV) can be used (Wildmann et al., 2013). Also, the use of a multicopter UAV with onboard temperature, humidity and gas sensors for in situ measurements of meteorological variables in the ABL was reported recently (Brosy et al., 2017).

In human medicine, the careful scientific evaluation of the actual concentration of pollen in the air is the indispensable basis for reliable pollen risk information. Inadequate forecasts concerning the expected pollen concentration are regarded as a considerable health risk for pollen allergy sufferers (Bastl et al., 2017). Damialis et al. (2017) reported just recently of the first basic experiments measuring pollen concentrations in considerable altitudes above ground level by using a manned aircraft. This research, however has shown, that the use of manned aircraft in densely populated areas is limited and further requires a considerable organizational and financial effort.

In environmental sciences, the pollution of air with fine particulate matter has been a problem for many years, in particular in urban areas with unfavourable geographical topography. The so-called

PM2.5 and PM10 particulate matter according to the National Air Quality-Standard for particulate matter of the U.S. Environmental Protection Agency (Vincent, 2007) as well as coarse particles have been chemically characterized (Hueglin et al., 2005). The samples were taken using pre-weighted quartz fibre filters, which were weighted again after collection of particles. This method requires considerable expenditure and processing time in particular for pre- and re-conditioning of the filters prior to the respective weighing step. The possibility of assigning health risks to specific classes of particulate matter has been investigated, but the results are not satisfactorily reliable yet (Harrison and Yin, 2000), not least because of the scarcity of measurement data, which are, in turn, related to the complex measuring methods. Further areas of greater interest in particle concentration in the air are the scientific fields of paleo-environmental and paleo-climatological reconstructions. Here, for example, the knowledge of the spatial and temporal distribution of pollen could help to improve the accuracy of paleoclimate models derived from pollen grains extracted from lacustrine or marine sediments (Shang et al., 2009).

For most of these applications, it would be highly desirable not only to count the number or measure the size of the particles as done with an optical particle counter (OPC), but also to identify the particles according to their type and/or chemical composition. In this regard, particle collection with subsequent particle-type identification and quantification is of advantage over particle counting at least as long as reliable in-situ particle identification is not available. First attempts to collect bioaerosol particles using a pollen trap mounted on a fixed wing UAV are described in Gottwald and Tedders (1985). Another way to realize the collection of airborne particles is to use a tethered balloon with rotating rods for capturing airborne pollen grains (Comtois et al., 2000). Since the balloon experiences wind drift, the possibilities of performing measurements at a predetermined position are limited. In addition, the air volume sampled by the rotating rods is determinable with limited accuracy only. Sticky surfaces carried by a fixed-wing autonomous UAV described by Schmale et al. (2008) and Aylor et al. (2011) allow long-range particle collection but provide only limited spatial resolution of particle concentration values. The sampled air volume, again, is determinable with limited accuracy only. In addition, the requirement of a runway for start and landing limits the potential use of fixed wing UAVs in urban or built-up areas.

Here we present the structural design and first application of a newly in-house developed particle collection system (PCS) operated onboard a commercially available multicopter UAV (Fig. 1) for in situ measurements of the concentration of pollen and spores in the ABL. Initially, a commercially available multicopter UAV that meets the requirements for payload capability as well as flight stability and reliability was selected and built from a kit. The multicopter UAV provides not only the possibility of the vertical take-off and landing, thus simplifying the application in urban areas, but – even more important – also the possibility of hovering and hence collecting particles at elevated positions that can be maintained with high precision. Then experiments were conducted to investigate the air flow pattern created by the UAV's propellers during hovering. The experimental results were used to determine the dimension and position of the air intake of the PCS on the multicopter UAV in order to provide substantially isokinetic sampling conditions.

An essential part of the present study was the development of a new PCS that can operate onboard the multicopter UAV despite the weight and power constraints. One major goal in the development of the PCS was to sample an air volume of 1 m^3 within 5 minutes in order to ensure a statistically evaluable number of collected particles even in the case of low particle concentrations in the air, and also to provide a high temporal resolution of the measurement results compared to other particle collection systems. This goal was achieved by using a powerful blower that delivers an air volume flow of typically 0.2 m^3 per minute (corresponding to 200.000 standard cubic centimetres per minute) through the PCS. Another challenge was to develop an impactor that ensures reliable separation of the aerosol particles even at these high air flow rates.

In order to determine the capability of the PCS operated onboard the multicopter UAV and to test the reliability of the entire new unmanned aerial system (UAS), several test flights were conducted at different altitudes over several days in March 2017. The collected particles were analysed and counted using light microscopy. Finally, the pollen concentration values determined with the PCS onboard the multicopter UAV were compared with corresponding data published by forecast information services such as the Stiftung Deutscher Polleninformationsdienst (PID) or MeteoSwiss.

5 Conclusions

The presented multicopter based UAS with the newly developed impactor-based particle collection system (PCS) operated in-flight and onboard the multicopter UAV has proven to be a powerful and reliable system for aerosol particle collection in the ABL. More than thirty particle collection flights were carried out with this new UAS, each with a sampled air volume of 2 m^3 and at flight altitudes of up to 300 m a.g.l..

A particle separation efficiency of more than 98 % was determined for the newly developed impactor-based PCS despite the high air volume flow of 0.2 m^3 per minute. In order to achieve a high particle capturing efficiency, the design and placement of the air intake was optimized by conducting and evaluating visual airflow tests. Easily interchangeable sample carriers guarantee a lean post-flight workflow with regard to visual analysis using transmitted light microscopy. The use of a laminar air flow box reliably protects the particle sample carriers from particle contamination during their manufacturing, handling, and storing.

Subject to a sufficiently high concentration of the corresponding particles in the air, the number of in-flight collected particles was regularly well above one hundred during a ten-minute sampling operation. These large numbers of collected particles provide the possibility of reducing the volume of sampled air and thus reducing the aerial sampling period. Accordingly, particle collection flights at altitudes of up to 500 m a.g.l. and beyond are possible without any modification regarding the multicopter UAV.

The particle collection flights carried out during the pollen season in March 2017 at altitudes of 25 m, 100 m, 200 m and 300 m a.g.l. show remarkable vertical distribution of the various pollen genera and impressively illustrate the scientific potential of the newly developed PCS operated onboard a multicopter UAV, such as the determination and modelling of the propagation behaviour of pollen, spores and other airborne particles in the ABL (Aylor et al., 2006). In a more application-oriented context, it is very gratifying that the pollen concentration values measured with the new PCS onboard the multicopter UAV matches very well, both in their absolute numbers as well as in their relative temporal change, with the pollen concentration predictions and pollen concentration data published by the two pollen information services Stiftung Deutscher Polleninformationsdienst (PID) and MeteoSchweiz.

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Attachment no. 2

figure and table captions

Figure 1. Multicopter UAV (DJI S900) in hovering flight with components of the particle collection system as indicated: air intake, impactor, mass flow sensor, and blower. The inlet is arranged about 30 cm above the propeller plane.

Figure 2. Newly developed particle collection system (PCS) with a complete weight of 600 g comprising (1) an air intake that allows the intake of ambient air under isokinetic-near conditions, (2) an impactor for extracting the particles from sampled air and depositing them on a sample carrier, (3) a mass flow sensor, located downstream of the particle extractor, measuring the air mass flow through the PCS, and (4) an electric blower generating the air flow through the components of the PCS. The components of the PCS and their connections are leak-tight. Air volume flow during operation is 200 slm.

Figure 3. Schematic longitudinal cross section through the impactor used as a particle extractor in the particle collection system. Particles are drawn through the pipe from the top towards the glycerine gelatine covered microscope slide. Glycerine gelatine highlighted in green, cross section of silicone O-ring in red. Mean impaction velocity is about 50 m s^{-1}.

Figure 4. (A) Perspective view on the assembled particle extractor, with connecting pipe being connected into the bellmouth-shaped air intake; (B) perspective view on the particle extractor with the upper housing part removed, and the sample carrier installed; (C) top view on the particle extractor with the upper housing part removed and particle loaded sample carrier; extracted particles are deposited in the area enclosed by the white plastic ring.

Figure 5. (A) Top view on a particle loaded sample carrier comprising a common microscope slide and a plastic ring with gelatine used as the particle embedding layer, covered with a transparent microscope cover slip (square). (B) Post-sampling treatment steps 1 to 4 of the particle loaded sample carrier to avoid contamination and allow preservation, shown as cross sections through a sample carrier. Highlighted in green: gelatine layer in which the collected particles (blue dots) are embedded. Step 1: Sample carrier immediately after particle collection with deposited particles exposed; Step 2: A drop of molten gelatine is placed onto the particle-loaded gelatine layer; Step 3: A cover slip is placed centrally on the drop of liquid gelatine; Step 4: The cover slip is lowered vertically to protect and seal the particle-loaded glycerine gelatine.

Figure 6. Investigation of the air flow pattern caused by the multicopter UAV (DJI S900) using three coloured pyrotechnical smoke cartridges with (A) flying the multicopter UAV below the lowest smoke plume, and (B) below the middle smoke plume; screen shots taken out of a 30 seconds video sequence. Side wind from right to left. Dilution of the smoke plume and thus mixing of the surrounding air occurs essentially only on the lee side and below the multicopter UAV, while in windward and above the multicopter UAV, the approaching plume remains largely unaffected.

Figure 7. Schematic sketch of the extraction efficiency experiment with two identical impactors (impactor 1 and impactor 2) connected in a cascade configuration to investigate particle extraction efficiency. At 100 % efficiency, all particles would be extracted by impactor 1, leaving no particle for impactor 2.

Figure 8. Overview of the possible influences of the different components of the newly developed particle collection system (PCS) on the finally determined particle concentration. The components of the PCS, at which the influences can occur, namely air intake, impactor, and mass flow sensor, are arranged along the horizontal axis. Influences that can lead to the determination of a particle concentration higher than the actual particle concentration are shown in the upper half of the figure (blue background), whereas the influences that can lead to the determination of a particle concentration lower than the actual particle concentration are shown in the lower half of the figure (red background).

Figure 9. (A) Microscope photograph of a sample carrier loaded with various aerosol particles deposited during a multicopter UAV collection flight at an altitude of 300 m above ground level. The section bounded by the cyan rectangle is shown enlarged in (B). (B) Enlargement shows clusters of *Corylus* and *Taxus* pollen grains as well as transparent mineral and opaque particles in various sizes.

Figure 10. Graphical representation of the measured concentrations of particles (in particles per m^3 of sampled air) collected during the aerosol particle collection flights on March 3, 10, and 16, 2017. Colour differences in the individual bars represent the particle concentration at different altitudes. It should be noted that only on March 3, 2017 a sampling

operation on ground has been carried out with the propellers of the multicopter UAV being switched off. On that date, sampling operations have been carried out also in altitudes of 25 m, 100 m, and 200 m above ground level (a.g.l.), whereas on March 10 and 16, 2017 sampling operations have been carried out in altitudes of 25 m, 200 m, and 300 m a.g.l., respectively.

Figure 11. Concentration of pollen of the genus Corylus and Alnus collected in Poltringen with the new particle collection system (PCS) operated onboard the multicopter UAV during hovering at 25 m a.g.l. on March 3, 10, and 16, 2017 in comparison with pollen concentrations of the same genus published by MeteoSchweiz in Zürich measured by using a Burkard pollen sampler. The lowest altitude above ground level data for Poltringen are available from 25 m altitude a.g.l. for all three sampling days.

Table 1. Aerosol particle collection flights carried out on March 3, 10, and 16, 2017 performed in different hovering altitudes.

Table 2. Number of pollen grains collected in impactor 1 and impactor 2 of the arrangement of Figure 7 for determination of the retention rate and thus the extraction efficiency of the newly developed impactor.

Table 3. Summary of the number of collected particles (from 2 m3 sampled air, respectively) using the new particle collection system (PCS) onboard the multicopter UAV during the aerosol particle collection flights carried out in March 2017 (top); in addition, the comparison of these measured values with the forecast data of the Deutscher Polleninformationsdienst (PID) (middle); and the pollen concentrations measured by MeteoSwiss measured by a commercially available Burkard pollen sampler in Zurich (bottom);

Attachment no. 3

table 3

Results of the Measurements performed at Poltringen Airfield with the newly developed Particle Collection System mounted on the multicopter UAV

	March 3				March 10			March 16		
collection start time (LT)	15:55	15:20	15:05	15:44	14:57	14:38	15:40	14:18	13:55	14:40
flight altitude (in m a.g.l)	ground	25 m	100 m	200 m	25 m	200 m	300 m	25 m	200 m	300 m
Taxus	32	22	24	2	113	133	70	135	175	88
Corylus	27	35	30	29	32	36	26	4	1	-
Alnus	128	167	159	181	109	91	63	18	11	12
Cyperaceae	-	-	-	-	5	2	2	-	-	-
Salix	-	3	2	1	9	3	5	23	3	10
fungal spores type 1	22	5	17	2	200	114	131	2	2	2
fungal spores type 2	16	1	3	4	3	4	4	2	5	3
Charcoal particles >20 µm	2	11	4	9	52	33	26	30	34	16

Comparison to the Statement of the Deutscher Polleninformationsdienst (PID)

	Statement of the Deutscher Polleninformationsdienst (PID) "Wochenpollenvorhersage"		
	Week of March 1, 2017 (KW9)	Week of March 8, 2017 (KW10)	Week of March 15 (KW 11)
Pollen of the genera Taxus	first weak load "erste schwache Belastung"	short time large amount "kurze Zeit große Menge"	the most abundant genus of Pollen "die mengenmaäßig haäufigste Pollenart"
Pollen of the genera Corylus and Alnus	first high concentration "erstmals hohe Konzentration"	approaches the end "nähert sich dem Ende"	fadet ("abgeblüht")

Comparison to the Measurements of MeteoSchweiz performed in Zürich

	March 3, 3017	March 10, 2017	March 16, 2017
Alnus		Number of pollen grains per m^3	
PCS in Poltringen (25 m a.g.l.)	18	15	2
Burkard sampler in Zürich	41	20	5
Corylus		Number of pollen grains per m^3	
PCS in Poltringen (25 m a.g.l.)	84	55	9
Burkard sampler in Zürich	39	45	8

Attachment no. 4

figure 10