Tampere University of Applied Sciences

Mobile measurement of aerosols using drones

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ABSTRACT

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The measurement of air particles is often restricted by its versatility. Remote or inaccessible areas are challenging to humans in terms of gathering measurable data. Unmanned aerial vehicles (UAVs) allow us to overcome this burden and gather valuable data to predict and analyse current air compositions, and with global application, anticipate potential future atmospheric processes.

This thesis provides the reader with general knowledge about aerosols and techniques for measuring them. Beyond that, the possibility to combine the measurement with advantageous UAVs is discussed, and an overview of previous attempts is given. By raising a sense of awareness regarding our air constituents and opportunities with future airborne measurement techniques, a greater understanding and possible problem-solving approaches are generated.

The content of this thesis shows that drones are immensely beneficial for enhancing the versatility of current measurement systems. Expanding the range of possibilities to measure aerosols in various remote areas is improving our knowledge about particle-climate interactions and helps us to control greenhouse gas induced climate heating and human health risks resulting from air pollution.

The increasing global particle emissions inspired the author of this thesis to analyse the use of current drone implementations in the process of measuring air constituents, and to illustrate possible tests to investigate the influences drones might have on the measurement reliability. Further study is needed to establish a reliable conclusion whether the planned tests are meaningful.

Key words: Particulate Matter, Aerosol, Drone, Rotor, Turbulence

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ABBREVIATIONS AND TERMS

m	Metre
mm	Millimetre
μm	Micrometre
nm	Nanometre
h	Height
τ	Relaxation time
C_C	Cunningham correction factor
N	Total amount of values
σ	Standard deviation
$^{\circ}\mathrm{C}$	Degree Celsius
η	Viscosity
d	Inner diameter
u	Flow velocity
ρ	Density
CO_2	Carbon dioxide
SARS	Severe acute respiratory syndrome
CoV-2	Coronavirus 2
AOD	Aerosol Optical Depth
BC	Before Christ, Black Carbon
CCN	Cloud Condensation Nuclei
IN	Ice Nucleation
IPCC	Intergovernmental Panel on Climate Change
LDD	Long Distance Dispersal
NASA	National Aeronautics and Space Administration
PM	Particulate Matter
TAMK	Tampere University of Applied Sciences
UAV	Unmanned Aerial Vehicle
WHO	World Health Organization
Drone	If not other stated, this term refers to a rotary wing UAV (Unmanned Aerial Vehicle)

1 INTRODUCTION

1.1 Research Purpose

The purpose of this thesis is to examine the fundamentals of aerosols. An aerosol is defined by a suspension of a liquid or solid particle in a gas, such as air. Whilst informing the readers about the different types of aerosols and their effect on our ecosystem and human health, it is desirable to spread a sense of awareness as well. Because of the ongoing industrialization and the patterns that come with it, the need to measure aerosols in our surrounding spaces, areas of high sensitivity, including our atmosphere and remote areas is increasing steadily. By that, also non-accesible areas are meant, defined by hazards or physical limations for human reachability. Therefore, the implementation of drones to meter local particle concentrations in those regions will be investigated to further observe and control inaccesible areas of high interest.

1.2 Research Aim and Questions

The research aim of this paper is to investigate the possbilities to pair the measurement of particle concentrations with the ability to access nearly any given area with drones. Due to the current SARS-CoV-2 pandemic, no practicle testing can be done but ideas of potential experiments will still be explained and discussed. It is to be indentified, if general measurement deviations between a hand-held and an airborne testing will occur. To avoid measurement errors due to blown up particles from the ground, the minimum required vertical distance to the surface will also be examined. Furthermore, a possibility to analyse the influences induced by spinning drone rotors on the airflow underneath the drone is descrbied. Lastly, a test to illustrate the measurement reliability in turbulent conditions is explained to show possible limitations of this type of measuring.

1.3 Validity

The objective of this thesis is to investigate the suitability of measuring aerosol concentrations using a drone to enhance versatility. If the above mentioned tests reveal requirements and results that support this type of measuring under certain conditions, the validity of it will be established.

1.4 Reliability

The reliability of the gathered data is strongly dependent on the type of instrument that is being used to measure and the overall measuring strategy. Together, these premises dominate the measuring approach and consequently control the achieved reliability as well. Whilst testing, the present circumstances of the immutable, local region, e.g. temperature, humidity, particle flow direction and velocity, among others influence the results. Lastly, systematic errors that reduce the accuracy of the measurement and random errors that deteriorate the reliability remain present. To further clarify the reliability of measured data is part of the thesis purpose.

1.5 Limitations

Naturally, this thesis work is subject to limitations. There is no absolute accuracy in the compiled and analysed data due to the presence of systematic and random errors. When considering the versatile advantages of a drone regarding its capabilities of reaching inaccessible areas, there are limitations as well. The mandatory technology of a drone is only to a certain degree heat, dust and vibration resistant. Also, the range of such a device is dominated by the accumulator efficiency and recharge possibilites. Concernaing this investigation in particular, the available instrumentation limits the potential measuring approaches significantly. Conclusively, the current SARS-CoV-2 pandemic and the available time to finnish this thesis, limits the margin of achievable tests and time to analyse each one.

2 THEORETICAL FRAMEWORK

2.1 Fundamentals of aerosols

The term aerosol derives from a suspension of liquid or solid particles in a gaseous medium. It resembles a two-phase system since it includes a suspended solid or liquid phase and a surrounding gas phase. Aerosols are ubiquitous and exist in various forms, such as dust, fume, smoke, mist, haze, fog, clouds and smog but also in resuspended soils, residuals from combustion processes, welding fumes, dust from brake pads, cigarette smoke, sea salt particles from ocean spray or dust from volcanic eruptions among others. They are formed by conversion of gases to particles or by decomposition of liquids or solids into smaller components. (Kulkarni et al., 2011, p. 3)

With the, especially in the last decades rapidly growing industrialization and the consequences for the economy and ecology, the need to measure aerosols has increased for many fields. Already back in 1700 an Italian physician, named Bernardo Ramazzini, described the effects of dust and fine particles on our respiratory organs (Franco and Franco, 2001, p. 1382). Analyses from the World Health Organisation (WHO) reveal that in 2016 $91\ \%$ of the world population was living in areas where the WHO air quality guidelines limits were not met (WHO, 2018). As shown by the WHO, air pollution alone causes about seven million deaths yearly and therefore places it amongst the top worldwide risks for human health (A. Prüss-Ustün et al., 2019). Statements like these are forcing the public health and air pollution monitoring organizations to work on ways to reduce current concentrations. Additionally, the climate is affected strongly. According to the Intergovernmental Panel on Climate Change (IPCC) as for 2019 there is a $5\ \%$ chance that the global temperature increase in this century can be limited to the $2\ ^{\circ}C$ that has been agreed by the United Nations Framework Convention on Climate Change (UNFCCC). (Lelieveld et al., 2019) But also the pharmaceutical and chemical branch relies on aerosols, like sprays, to treat various rasporatory diseases. Without the use of aerosol inhalation many medical conditions could not be treated as well. (Hickey, 2019) Not least, medicine related matters must often consider the right handling of aerosols, as the WHO warns at the moment of the development of this thesis that the currently present pandemic SARS-CoV-2 virus infection risk rises due to airborne virus transmission with aerosols (WHO, 2020).

The typical size range of relevant aerosols is from 10^{-9} to $10^{-4}\ m$, that is, $1\ nm$ to $100\ \mu m$. Larger particles than that settle too quickly to be part of a substantial suspension of interest. The size of a particle is by far the most important characteristic, since it determines the behavior of the particle itself and also due to different forces. The average size of a single air molecule is approximately $3.7 \cdot 10^{-10}\ m$. Particles that are only slightly larger than that are governed by the Brownian motion. Whereas if their size is within a few micrometers they are dependent by gravitational and intertial forces. The size is also strongly affected by the present adhesion forces. Van der Waals forces let aerosol particles that contact each other usually adhere to one another and form agglomerates. Van der Waals forces can be described by a temporary shift in the electron density that leads to dipols and therefore generates charges that attract or repell nearby particles. That force lets them adhere to walls and surfaces as well. This is especially of interest when working with filters or any instrument in which the aerosol has to travel through small inlets that may attract it and cause adhesion. This characterisitc is the main difference from aerosols to gas molecules. (Kulkarni et al., 2011, pp. 4–8)

In the field of particle science it is mandatory to consider the shape of the particles. Sperical particles can be unmistakingly described by their diameter. But due to the side effects of condensation of liquid that is part of the particle’s growth, most atmospheric particles that also account to the air pollution are irregular shaped. (Kulkarni et al., 2011, p. 6) To still be able to compare sperical and non-sperical particles an equivalent diameter is defined. Depending on the measurement technique or what particle property is relevant, this definition expresses a size description that suits the purpose and is comparable to others. According to the International Union of Pure and Applied Chemistry (IUPAC) the equivalent diameter of a non-sperical particle is identical to a diameter of a spherical particle and also shows the same geometric, optical, electrical or aerodynamic behaviour. In laminar flow cenarios it can also be referred to as the Stokes diameter. (Nič et al., 2009, p. 2184) Exemplary, a few of the most commonly used equivalent diameters is the equivalent aerodynamic diameter of a sphercial particle that is expressed with the density unit and has the same settling velocity as that of the particle in question. It is relevant for particles bigger than $0.5\ \mu m$ that show some considerable inertia. Smaller particles than $0.5\ \mu m$ are often described by the equivalent diffusive diameter. It is the diameter of a particle that has the same diffusion coefficient as the particle under consideration. An equivalent optical diameter is defined by the diameter of a particle having the same response in an instrument that detects particles by their interaction with light rays. (Kulkarni et al., 2011, p. 41)

2.2 Size Distribution

Particulate matter is rarely homogenous in size. A variety of different formation processes are responsible for their growth and give them their size and shape. The shape can be divided into isometric form, platelets and fibres. Isometric describes a particle that has three approximately equal dimensions, forming a spherical particle. Platelets are defined by two long dimensions and a third smaller one. That can be leafes, discs or shreds. Fibres only have one long dimension and two much shorter ones. That could be a needle, blade or asbestos. (Colbeck, 2014, p. 5) If the particles within an aerosol, are similar sized, the aerosol can be called monodisperse. Their spread has to be below $10–20\ \%$ and due to this minor range, these particles are mostly formed by laboratory operations. If the spread is higher than that, the aerosol defines as polydisperse. Obviously, in both categories there is some range in size.

To manage the analysis of populations quantatively, it is mandatory to have a scientific defnition of their size distribution. (Kulkarni et al., 2011, p. 42) There are three main ways to categorize these. They can be defined by their modal distribution (Hinds, 1999), the 50% cut-off diameter or thirdly, by their dosimetric variables that can be related to human exposure by particles (Colbeck, 2014, p. 6). In the first case the most frequent way to use mathematical analysis is the lognormal function. This method has been acknowledged due to many years of emipircal data collection but mainly the reason being, that there are far more small particles than large ones. Each time a particle gets split into two pieces its quantity doubles and size halves most of the time. The following Figure 1 emphasizes this occurrence.

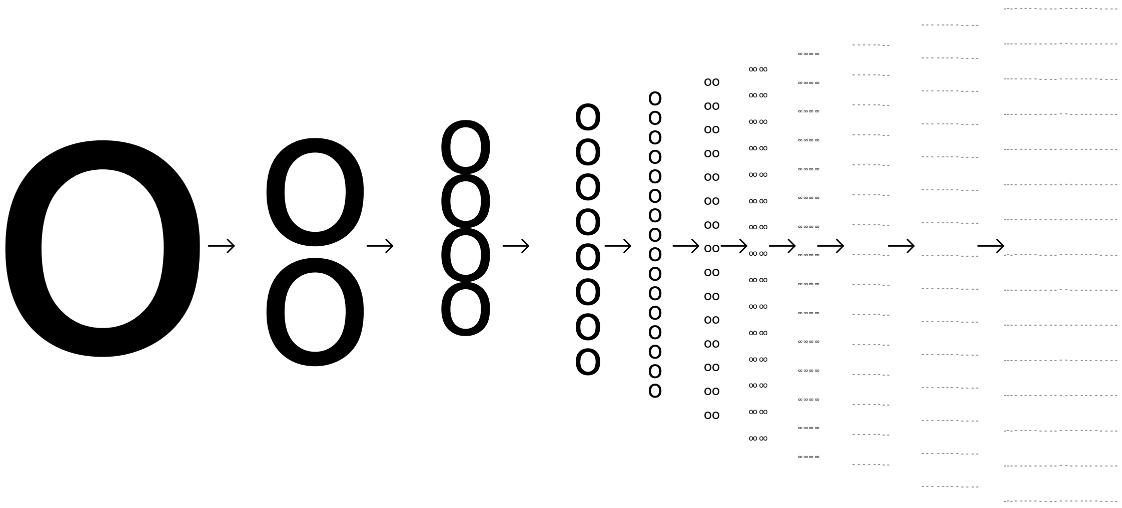

Figure 1: Rapid incremental duplication of an object (Own Creation)

In the past a common representation of the ambient particle size distribution was that of Junge (1963). He demonstrated the logarithm of particle number concentration against the logarithm of particle radius with a simple physics law. Later, Sverdrup and Whitby (1977) transformed aerosol number distributions to the ones of volumes. It showed three distinctive size modes, visiable as peaks, which they named nulcei, accumulation and coarse mode. Despite the various formation processes and therefore different characterisics forming, this representation proved itself to be efficient and accurate. It is nowadays a fundamental basic to understand the properties and behaviour of ambient aerosols, that often appear in the form of atmospheric aerosols. (Kulkarni et al., 2011, p. 43)

Atmospheric aerosols, that are, solid or liquid particles, suspended in the surrouding gas embodied by the atmosphere. Also, hydrometeors, like cloud droplets, ice crystals, raindrops, snowflakes and graupel can be classified as atmospheric aerosols, depending on the definition. (Boucher et al., 2013, p. 576) This will be further discussed in chapter 2.3.5 of this elaboration. As for the former mentioned modal size distribution by Whitby it describes a trimodal dispersion. The nuclei mode ranges from 0.005 to $0.1\ \mu m$, the accumulation mode from 0.1 to $2\ \mu m$ and the coarse mode includes everything greater than that. Conventionally, they are all plotted by a lognormal function. Whitby classfied the particles further into sub-categories, because ambient particles generally have their minimum concentration between the accumulation and the coarse mode. Particles with a diamter above $2\ \mu m$ are coarse and below that they are treated as fine particles. These two sub-categories have substantial dissimilarities in their origin and physical as well as chemical properties. The fine particles, as in nuclei mode, form from different combustion processes, condensation and coagulation and further photochemical reaction. The nuclei mode quickly growths up to the size range of the accumualtion mode that is mostly domianted by droplets formed by chemical conversion of gases to vapor which then condense. Lastly, coarse particles above $2\ \mu m$, that are, dust, sea salt spray and diverse biological residuals like plant constituents. (Kulkarni et al., 2011, p. 45) Less freuqently, another subdivision between the nuclei and the accumulation mode, is defined. The Aitken mode, also known as nuclei-atiken mode, connects the nuclei mode with the accumulation mode, covering the size range from $0.02\ \mu m$ to $0.2\ \mu m$. (Kulkarni et al., 2011, p. 382)

Further, aerosols can be categorizied by their $50\ \%$ cut-off diameter. Impactors are being used to separate particles of diverse size to their aerodynamic diameter. An impactor is distinguished by its cut-off sizes. It is commonly correlated to the Stokes diameter, that is, a diameter of a hypothetic hard sphere, having the same diffusive characteristic in a solution as the particle of interest. (W.H. Freeman, 2006, p. 766) The $50\ \%$ cut-off diameter is the cut-off size that achieves 50 % efficiency, because the components for example impactor blades naturally do not have a perfect characteristic. Thus, some particles of smaller or greater diameter are not being affected. To further guarantee separation, multi cascade impactors are often used that supply multiple stages. (Stec and Hull, 2010)

Finally and often used in particle science reports are the terms PM$_{2.5}$ and PM$_{10}$. The denotation of PM derives from particulate matter and is habitually used to describe air pollutants. (Visscher, 2014, p. 37) According to the European Commision, PM$_{10}$ resembles particulate matter that passes through a selected sampling inlet with a $50\ \%$ efficiency cut-off at $10\ \mu m$ aerodynamic diameter (European Commission, 2008). PM$_{2.5}$ is described in the same way. The reason behind this size separation of particulate matter refers to the severe impact of small particles on the human respiratory tract. The smaller particle size range can be further termed as fine and ultrafine that are both below a diameter of $2\ \mu m$. Especially, ultrafine particles that mainly get classified in the nuclei mode, resemble a tremendous risk to penetrate the deep lung tissue and consequently affect the human health. (Kulkarni et al., 2011, p. 48) The following Figure 2 shows a number of aerosols and their physical as well as health-realted properties.

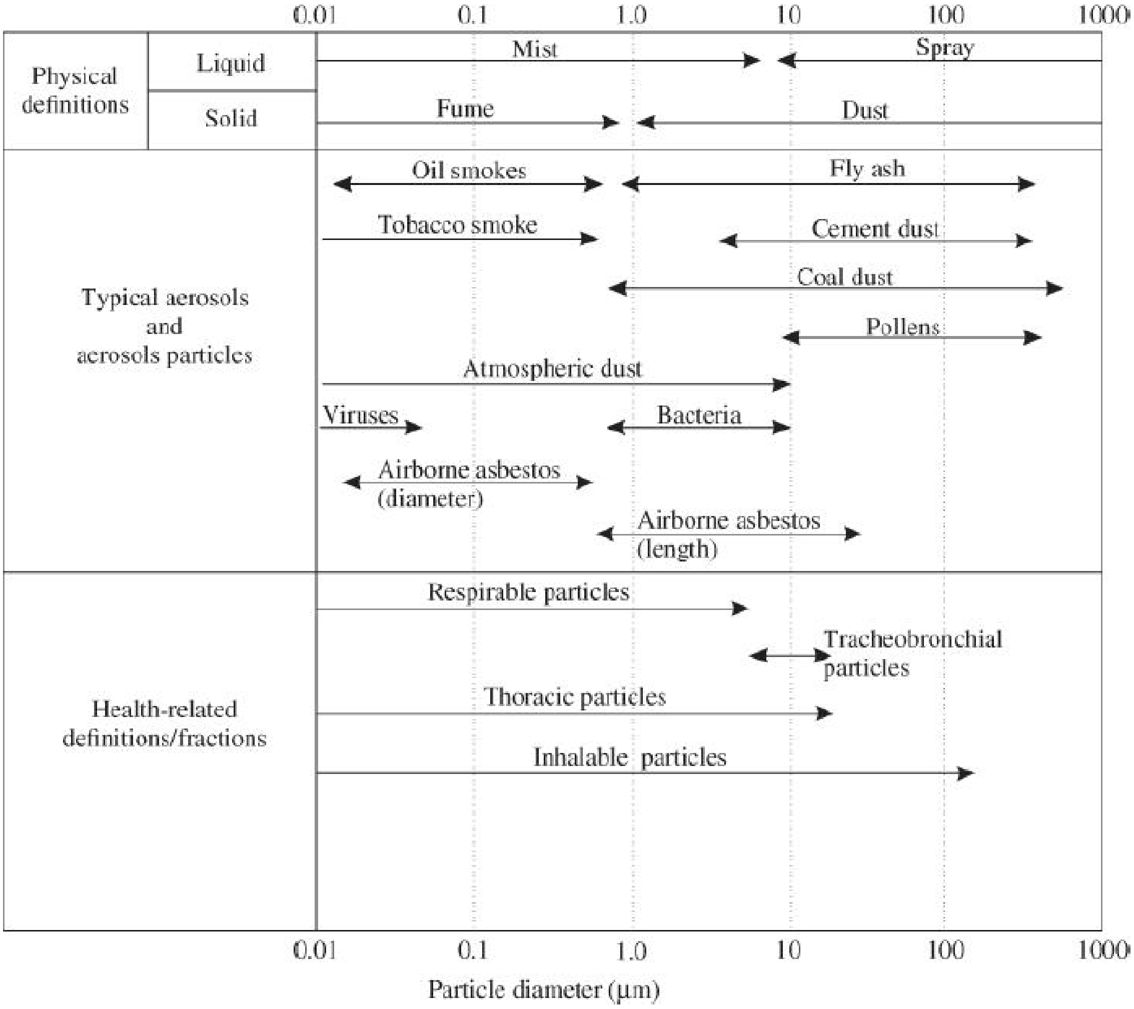

Figure 2: Particle size range categorized in subdivisons (Colbeck, 2014, p. 7)

It illustrates many common particle types from conventional sources like coal porcessing industries, combustion residuals, tobacco smoke and construction site materials that can not only be inhaled but also penetrate the human respiratory tract.

2.3 Types of aerosols

The extent of diverse aerosols is wide-ranging. They occur in various places, concentrations and sizes. Many times, us human interact with them without even noticing, mostly because we rely on our senses. If we cannot see or taste any unusual high concentration or type of particles, we are oblivious. Hence, it is mandatory to raise awareness amongst everyone because they are affecting our everyday life in many ways, whether we notice them or not. Not only former explained health issues or the effects on climate, but also the Earth's radiation budget demonstrated by Coakley et al. (1983), general visibility, as it has been investigated in various reports of Indian and Chinese cities by Cao et al. (2012), Lin et al. (2014), Singh and Dey (2012) and the environment are affected areas. Already, in the year 44 BC people linked the bad harvests on the effects of the volcanic eruption of the Etna (Forsyth, 1988).

2.3.1 Natural organic aerosols (Bioaerosols)

The term ”Bioaerosols” derives from biological aerosols and belongs to the atmospheric particles. Their size range is, as ordinary, $0.01\,\mu m$ to $100\,\mu m$ and they originate from the Earth's biosphere, that is, the entirety of all ecosystems (Thompson and Gates, 2018). Bioaerosols can be dead or alive organisms, like algae, bacteria and viruses or fragmental units, like fungal spores or pollen. (Ariya and Amyot, 2004; Castillo et al., 2012; Després et al., 2012; Gong et al., 2020; Graham et al., 2003; Tesson et al., 2016; Womack et al., 2010)

They can be further sub-categorized into primary and secondary biological aerosols and biogenic aerosols. Whereas, primary ones comprise organisms and intact cells, both living and non-living, secondary result from supplemental various physical and chemical processes. These can be condensation or oxidation among others and both have to be distinguished from biogenic aerosols. They are products from metabolism, that is, resulting products from the activity of living organisms (NASA, 2005) and commonly further chemical reactions that finally result in their footprint on the atmosphere. Volatile organic carbons, for example, methane or dimethysulfide account to them. (Colbeck, 2014, p. 393)

The knowledge about the long distance travel capabilities of diverese fine particles resembles an additional risk of increased infection risks globally. Long distance dispersal, in short LDD, has been investigated both, in horizontal dimensions by Brown and Hovmøller (2002), Nagarajan and Singh (1990) and in vertical dimensions by Nicolás et al. (2014), Wainwright (2015) and revealed the enourmous potential of fine particle spread. Some key findings are the presence of microorganisms in the free troposphere and stratosphere as well as possibly infection causing pathogens at a horizontal distance of at least $1000\,km$ and general continent crossing dispersal of microorganisms. Although there are many circumstances that could cause damage to living organism at such heights, for example, the increased exposure of ultraviolet radiation, low temperatures, dryness and low pH in clouds, many microorganisms developed the capacity to survive such extreme conditions as it is part of their sophisticated biology. (Burrows et al., 2009; Colbeck, 2014, p. 407) Given this knowledge it is standing to a reason that the global LDD of fine particles, including microorganisms or even viruses could lead to a potential risk enhancement of infection.

In fact, in the last two decades, since the occurence of the severe acute respiratory syndrome (SARS-CoV) 2003, the reappearance of the avian influenza virus H5N1 in 2003 and reemergence in 2009 of avian H1N1, also known as bird flue, the Middle East respiratory syndrome (MERS) in 2012, the avian H7N9 in 2013, the Ebola virus outbreak in 2014 and the reoccurence of the current SARS-CoV-2 pandemic in Dezember 2019, the possibility of aerosol transmission of infectious organism has been continiously investigated. In the first month of the pandemic it was difficult to precisely detect the exclusive affect of aerosol transmission, especially within health care facilities, though the data shows clear enough results that state this possibility should not be overseen and thus the idea of aerosol transmission for diverse infectious operators has been well established and many provisions have been made. (Tang et al., 2015)

However, at the present time doubts have vanished and clear evidence have been found. According to comprehensive investigations from Chang et al. (2020), Chan et al. (2020), Sabino-Silva et al. (2020) and Wang and Du (2020) there is a definite increase in risk of infection for health-care workers and dentist that commonly use aerosol generating processes. Moreover, the SARS-CoV-2 virus is proven to spread via respiratory droplets, contact with body fluids, contaminated surfaces and aerosol transmission (Chang et al., 2020; Liu et al., 2020; Moriyama et al., 2020; Sabino-Silva et al., 2020). The uncertainty about the capability of the SARS-CoV-2 virus aerosol transimisson was never from enormous extent, since other pandemic virusses, like SARS, MERS, H1N1 and other seasonal viral respiratory infections have been found to be able to spread via aerosols (Adhikari et al., 2019; Kulkarni et al., 2016; Tran et al., 2012; Yu et al., 2004; Zhang et al., 2013).

Obervations of Liu et al. (2020) reveal the presence of the SARS-CoV-2 virus in patient common rooms and toilets. Therefore, it has been advised to perform regular room ventilations, try to stay in open spaces and sufficient desinfection is necessary to control these areas. The currently present virus is known to remain present and infectious in aerosols for three hours. On contamined surfaces, e.g. plastic or stainless steel, it enhances up to 72 hours. (van Doremalen et al., 2020) Lately, these investigations have been vital to further understand the behaviour of virus spread and deal with challenging pandemics by minimizing infections.

2.3.2 Natural inorganic aerosols

Besides the natural organic aerosols there are various natural inorganic aerosols. Exemplary, there are sea spray, mineral dust, desert dust, volcanic minerals, black carbon and radioactive particles. Sea spray is mainly composed of sea salt fragments and some organic marine matter. The marine particles average in diameters of $200\ nm$ and smaller. (Leck and Keith Bigg, 2008; Russell et al., 2010, p. 6656) A report of the IPCC quotes the sea salt aerosol contamination can make up to 50 to $70\ \%$ of the total aerosol mass in oceanic remote sites and the occurring sizes of the particles are allocated in the coarse and accumulation range (Boucher et al., 2013, pp. 595–605). The constituent and concentration of sea spray is likely to be affected by surface wind speeds that resemble winds measured at a height of $10\ m$ above the main sea level (MSL), atmospheric stability, precipitation and ice coverage of the sea (Struthers et al., 2011). Since climate is one of the main factors influencing the sea spray concentrations, it is desirable to predict its future. However, the estimations regarding this are multifarious as shown by an IPCC report from (Boucher et al., 2013). Exemplarily, it is foreseen that because of an estimated reduction of sea salt emissions, deducted from the easing of the zonal mean surface wind speeds, a $19\ \%$ reduction in global sea salt burden from year 2011 to the year 2100 will occur (Liao et al., 2006, p. 12). Another analyse of various IPCC climate models reveal no sensitivity to varying sea surface temperatures but perhaps serve sensitivity to differing mean ocean winds because of future climate changes (Mahowald, Lamarque et al., 2006, p. 10). Following, Jones (2007) and Bellouin (2011) predict a significant increase of sea spray burdens, in detail, Jones anticipates a $51\ \%$ growth, both stating a rising $10\ m$ wind speed within the next 70 to 80 years (Bellouin et al., 2011, p. 8; Jones et al., 2007, p. 8). The assertions about the extent of future wind speeds are differing a lot, complementary, Young et al. (2011) assumes that the observed recent changes may have a different outcome as expected. This also concludes to a rather small credibility in the overall anticipated climate-induced predictions for the sea spray burden.

On the other hand, mineral dust dominates the overall aerosol mass over many continental areas, for example, South Asia and China, reaching $35\ \%$ of total aerosol mass with diameters below $10\ \mu m$ (Boucher et al., 2013, p. 596). It is allocated in the coarse mode, with a tendency to even bigger size ranges, with a small margin in the accumulation mode. Its main sources are wind erosion soil resuspension also some agricultural and industrial processes, like kicked up dust plumes from heavy machineries or cement powders. Because these particles are rich in nutrients and other vital organic matters the wind erosion causes severe land degradation of agricultural areas but encourages oceanic areas with its advantages, once it is diffused into upper levels of the atmosphere by strong winds. (Mysak et al., 2009)

How the climate change is going to affect mineral dust aerosols is again uncertain as, once more, shown by an IPCC report from (Struthers et al., 2011). Whereas, a study on the future margin of mean atmospheric dust loading from bare soils revealed an increase by a factor of more than three (Woodward et al., 2005, 4), others state an approximate steadiness with fluctuations around 10 – 20 % increase or decrease (Jacobson and Streets, 2009, p. 17; Tegen et al., 2004, 4). In comparison to the severe increase predicted by Woodward et al. (2005), there is a study foreseen a decrease of about 60 % because of estimated doubling CO_2 concentration (Mahowald, Muhs et al., 2006). This high variation of statements speaks for a lack of confidence in these forecasts.

Also, desert dust accounts to these kinds of minerals. The easily erodible dry soils of a desert make it easy for strong winds to kick up large amounts of fine particles. Again, these desert particles are a vital source of nutrients for oceans and other nutrient consuming areas. (Mahowald et al., 2014) The main desert dust sources are Africa, China and Mongolia as they provide some of the biggest and warmest climates on Earth (Shao et al., 2011, p. 187). Since about 60 % of the Earth is covered with clouds and the characteristic of desert dust to be hydrophobic, the effect it can have on the clouds and thus the Earth's climate is substantial (Shao et al., 2011, p. 190).

Just as deserts, volcanoes are another inevitable natural constituent of our planet. The Ring of Fire, also known as the Circum-Pacific Belt, describes the encircling area around the Pacific Ocean distinguished by frequent occurring earthquakes and by that nature present active volcanoes. Its most formative characteristic is the coverage of a substantial amount of frequently moving tectonic plates. 75 % percent of Earth's volcanoes, collectively accounting for 450, and a total of 90 % of Earth's earthquakes find their origin on the Ring of Fire. (National Geographic Society, 2019)

As they are an uncontrollable fine particle source, it is important to not underestimate its presence. Strong volcanic eruptions are able to spread particles up into the stratosphere. Following, because of the additional sunlight reflection, this has a cooling effect shaping large climate areas of the Earth. (Crutzen, 2006, p. 212) This cooling effect is also stated by others, predicting a global cooling of 0.05 to 0.12 °C since 2000 (Ridley et al., 2014). For the most part, the sulphates that are dispersed by volcanic eruptions, are thought to have these mentioned impacts on the global climate (Driscoll et al., 2012; Llanillo et al., 2010; Stenchikov, 2002). Considering the former mentioned improbable 2 °C limit on global temperature increase, stated by the IPCC in 2019 for this century, set by the United Nations Framework Convention, the influence of the cooling effect by volcanic particles in high altitudes in the last 20 years already accounts for 2.5 to $6\ \%$ of that limitation and therefore represents a source that commands mindfulness.

Apart from the cooling effect, ash clouds, dispersed by severe volcanic eruptions, reaching lower stratospheric levels, endanger aviation safety. Only between 1980 and 1990, there were approximately ten serious eruptions making this to a relevant topic for aviation briefings. Not only are the ashes already hazardous for planes, but the clouds carry corrosive gases and rocks the size of a few centimetres in diameter. Aircrafts passing through them suffer external erosion and engine failures. Especially, the drift of ash clouds and night flights, reducing the chance of spotting them, play a vital role in aircraft-volcanic ash cloud interactions. (Casadevall, 1993)

Radioactive material represents a determined source for harmful aerosols. Besides the industrial use of radioactive nuclides there are many natural sources in our everyday life as well. Cosmic rays are interacting with our atmosphere, producing radionuclides like ^{14}C (Carbon-14) or ^{7}Be (Beryllioum-7). The scattering of soil particles spreads incorporated radionuclides like ^{40}K (Potassium-40), ^{235}U and ^{238}U (Uranium-235/238), ^{232}Th (Thorium-232) and their natural decay products that are a constituent of phosphate fertilizers. Also, radiation from soils and materials in use for buildings and constructions contain ^{222}Rn (Radon-222) that is another decay product from uranium and ^{220}Rn (Radon-220) from the thorium decay series and ^{219}Rn (Radon-219) from the actinium decay series. (Eisenbud and Gesell, 1997, pp. 172–175; Kulkarni et al., 2011, p. 637)

^{210}Pb (Lead-210) and ^{210}Po (Polonium-210) are decay products of Radon-220 and have both been measured in tobacco leaves and smoke (National Council on Radiation Protection and Measurements, 2009). That smoking plays a meaningful role in radioactive exposure for humans is shown by many researches. Per cigarette, there is an average of $14\ mBq$ of which $70-75\ \%$ gets transferred to the smoke and filters do only reduce it by $2.5-5\ \%$ (Khater, 2004; Skwarzec et al., 2001). Naturally, the amount of smoke being inhaled actively or by others passively differs strongly from case to case. The insights of numerous reports reveal that the annual effective dose for a 20 cigarette per day smoker averages $0.36\ mSv$ (National Council on Radiation Protection and Measurements, 2009, p. 162) Thereby, the legal annual effective dose limit for the normal population is $1\ \frac{mSv}{an}$ in most countries around the world (BfS, 2019; Canadian Nuclear Safety Commission, 2019; World Nuclear Association, 2018). To bring this into perspective, $36\ \%$ of the annual maximum dose only comes from smoking, that is for most people not ordinarily considered to be a high radioactive exposure risk.

Apart from soils, fossil fuels contain various radioactive nuclides that get dispersed by combustion processes (Eisenbud and Gesell, 1997, p. 175). The most obvious radioactive aerosol exposure comes from power fuel cycles of nuclear power plants and unforeseen occurring accidents, like Chernobyl 1986 and Fukushima 2011 as they represent some of the most notorious ones. Additional accidents with diverse sources, for example, nuclear submarines, unreasonable nuclear waste management or open-air tests, likewise account to high exposure origins (Eisenbud and Gesell, 1997, 210 et sqq.). Even without the influence of humankind, radon is a radioactive element and its short-lived daughter nuclides are dispersed in the air, creating hazardous aerosols. Especially, for miners this nuclide is from exceptional risk, but the general population is exposed to it, too. (Füri et al., 2020) In fact, it represents the second most important cause of lung cancer besides smoking. 3 to $14\ \%$, averaging at $8.5\ \%$, of all lung cancers are linked to the effects of inhaled radon. The variation is due to the high differences in radon concentrations among countries and measurement methods. (WHO, 2009)

Lastly, black carbon (BC) also contributes to the primary aerosol sources like the former, that is aerosol particles directly dispersed into the atmosphere, whereas secondary aerosol particles need additional chemical reactions to do so (Hinds, 1999, p. 8). BC is one of the most dominant absorbers of solar radiation in the atmosphere in the visible spectrum (Ramanathan and Carmichael, 2008). It is a component of fine particulate matter with a smaller aerodynamic diameter than $2.5\ \mu m$ and is emitted in both ways, anthropogenic and naturally. The natural occurrence of BC is often linked to soot as it is a product of incomplete combustion processes, such as the burning of diverse biomasses, wildfires, car engines, decisive diesel engines, industry and many more origins. (Anenberg et al., 2012, p. 831)

Apart from the reduction in visibility, radiative impacts and correlation to other trace gases of BC, that has been investigated by several studies, including surface measurements by Wang et al. (2011), Wang et al. (2018), Zheng et al. (2019) and vertical measurements by Hu et al. (2020), Zhao et al. (2019) are correlated to premature mortality and severe impacts on Earth's climate. It is estimated that by implementing adequate provisions the global population-weighted average surface concentration of $PM_{2.5}$, targeting BC, could be reduced by $23-34\ \%$. That could save the global premature deaths of $0.6-4.4$ million people until the year 2030. Thereby, only Asia is expected to account for at least $80\ \%$ of them. (Anenberg et al., 2012)

2.3.3 Anthropogenic aerosols

Anthropogenic aerosols are particles dispersed within a gaseous medium through human actions. Most of the previous mentioned BC is anthropogenic origin making it an important factor regarding the climate balance with mainly contra-productive properties. However, some indirect cooling possibilities are further discussed in chapter 2.3.4. To give a comparison, an even stronger climate influencer represents carbon dioxide (CO_2) as it can last suspended in the atmosphere for centuries, whereas BC only does for one to two weeks. (Bloudoff, 2013; Bond et al., 2013, p. 5381; Rosenthal, 2013) CO_2 is the main anthropogenic greenhouse gas and accounts for about $60\ \%$ of the anthropogenic greenhouse effect (Visscher, 2014, p. 41). Though it is to be mentioned that CO_2 cannot be classified as a traditional aerosol since it is a gas and not particulate matter suspended in a gaseous medium. Still, there are CO_2 aerosols finding use in biologic laboratory experiments, for example, removing biofilm or proteins from various substrate surfaces (Cha et al., 2012; Kang et al., 2010; Singh, Hong, Jang, 2015; Singh, Monnappa et al., 2015).

Another typical anthropogenic aerosol, that is commonly linked to combustion related emissions is sulphate. They account for about $10 - 30\ \%$ of the total aerosol mass in most areas. Thus, in rural areas of Africa, urban Oceania and South America their share is lower, not exceeding $10\ \%$. Its size range covers the Aitken to coarse mode and rarely the nuclei mode as well. The sources of sulphuric particle emissions are mainly marine, combustion processes and volcanic eruptions but also the oxidation of sulphur dioxide (SO_2) from natural and anthropogenic sulphur gases to SO_4. (Boucher et al., 2013, p. 597; Colbeck, 2014, p. 187) The importance of sulphates as a potential efficient driver for global warming retardation is acknowledged by various atmospheric scientists like Baker et al. (2015) and Soldatenko (2018, p. 8212) In fact, it is thought that if SO_2 and carbonaceous aerosols are being removed, the Earth's climate can warm up by more than $0.5°C$, predominantly because of the induced cooling effect of sulphate (Samset et al., 2018).

Related to sulphur are nitrate aerosols. They are chemically formed in the atmosphere in combination with ammonia, just like sulphuric aerosols and are thus strongly dependent on ammonia sources and atmospheric sulphur concentrations in the future. The main source of it is the oxidation of nitrogen oxides (NO_x) and industrial combustion processes or the burning of biomasses and fossil fuels. Following to these sources, its particle size ranges between the accumulation and coarse mode. (Bauer et al., 2007; Boucher et al., 2013, p. 597; Feng and Penner, 2007, p. 4)(Bauer et al., 2007)(Bauer et al., 2007)(Bauer et al., 2007)(Bauer et al., 2007) The effects of nitrate aerosols on the climate are rather small, as they do not account to the greenhouse gases. It resembles an air pollutant and pollution levels similar to the ones of sulphur. (Bauer et al., 2007) There are various global studies on the radiative effects of nitrate and ammonium aerosols, emphasising the relevance for the Earth's climate balance (Adams et al., 2001; Jacobson, 2001; Liao, 2004). Referring to Rafferty, Tikkanen et al. (2020), just as sulphate, nitrate aerosols reflect incoming sunlight and thereby reducing the global temperature.

Adjacent to this, ammonium accounts as another anthropogenic atmospheric aerosol. Its source being mostly excreta from wild and farm animals, synthetic fertilization, oceans, biomass burnings and the human population including pets, sets its size range in between the accumulation and coarse mode. (Bauer et al., 2007) A decrease of anthropogenic sulphate aerosols, investigated by aircraft observations in Europe by Haywood et al. (2008) concludes according to Baker et al. (2015) an increase in ammonium nitrate aerosols because of the higher availability of ammonia, considering the fact, that nitrate and sulphuric acids both need ammonia to form ammonium nitrate and ammonium sulphate (Bellouin et al., 2011, p. 4; West et al., 1999).

Concluding, nitrate, sulphur and ammonium all three account to secondary inorganic aerosols with rather anthropogenic origins (Long et al., 2014). Radioactive aerosols have been discussed in the previous chapter. Nevertheless, it should be mentioned that anthropogenic radioactive particle emissions are present. Multiple reports reveal the contamination levels and radioactive aerosol concentrations of the Chernobyl explosion 1986 being carried over vast distances due to the wind (Ogorodnikov et al., 2004; Ogorodnikov et al., 2006), Fukushima accident 2011, dispersing particles globally and getting noticed in France (Evrard et al., 2012) and other radioactive accidents that are not further mentioned.

2.3.4 Atmospheric aerosols and their environmental impact

All the above-mentioned aerosols account to atmospheric aerosols as they are suspended in the atmosphere. In the former chapters many influences of specific atmospheric aerosols have been discussed and this chapter focusses on the common effects of atmospheric aerosols on the climate and humans.

Atmospheric aerosols derive from natural and anthropogenic sources and have the ability to affect the Earth’s climate in various way. The most known effects are their radiation forcing, by either scattering or absorbing light and interaction with clouds. Particles that scatter sunlight are detaining radiation from reaching surfaces and therefore infuse a local cooling effect. By atmospheric air circulations the cooling effects get further distributed. In general, this phenomenon is known as albedo. Albedo is Latin, translating to whiteness and describes the amount of sunlight getting reflected from surfaces, such as the ground, clouds, snow, sea ice and deserts. (Coakley et al., 2003, p. 1914; Law and Rennie, 2015)

The complement to that is when particles have the characteristic to absorb sunlight. This leads to a temperature increase for the aerosol particles and local cooling for the surface, again due to less radiation reaching the surface. After various air circulation and mixing processes the thermal energy gets distributed evenly, resulting in a warming effect for the surface. (Boucher et al., 2013, p. 623) As most atmospheric aerosols have the characteristic to reflect sunlight, they feature a cooling effect that is counteracting the global warming induced from the greenhouse gases (Rafferty, Cunningham et al., 2020; Rafferty, Tikkanen et al., 2020).

This occurrence has been investigated in multiple regions across the globe, especially in areas that are highly affected by immense atmospheric aerosol concentrations or areas from significant interest relating the Earth’s radiation budget, like the poles. Mueller et al. (2018) has verified that the aerosol cooling effect is masking substantial parts of the greenhouse gas induced Arctic ice decline. The rise in global temperature results in melting of the Arctic and Antarctic ice caps, whereupon the Earth’s capability to reflect incoming sunlight reduces and further melting occurs. The aerosol cooling effect is estimated to have offset approximately $60\ \%$ of the estimated greenhouse gas induced warming in the Arctic over the period of 1913 to 2012 and globally about $27\ \%$ from 1951 to 2010 (Najafi et al., 2015). In addition, Norway scientists claim to evaluate the total warming equalization due to the cooling effect on $60 - 70\%$ (Arvesen et al., 2018). In areas of exceptional high atmospheric aerosol concentrations, the advantages are even more reasonable. China’s heavy aerosol pollution of $PM_{2.5}$ is reducing direct radiant exposure by $89\ \%$ and thereby lessen the surface temperature. This temperature decrease is mainly due to the emergence of inversion in the vertical atmosphere stratification. (Zhong et al., 2018) Many more reports and projects show the partially immense impact of the aerosol cooling effect on the surface temperatures. Consequently, it is likely that the temperatures will further increase when applying the planned decreases of anthropogenic aerosols in the future time to fulfil the air quality policies. (Boucher et al., 2013, p. 622)

Complementary to the atmospheric aerosols cooling the climate due to their reflective characteristics, BC is known to be responsible for its immense global warming impact, just next to the effects of the greenhouse gas CO_2. Several reports are stating that behaviour of BC in our atmosphere (Lovell, 2013; Zhuang et al., 2018), some estimating temperature increase in China between 1951 and 2000 due to direct radiative forcing of $0.62\,°C$ (Chang et al., 2009).

To further understand the physics of climate effects by fine atmospheric particles it is important to understand, that they do not appear in distinct exclusive groups but rather in a mixing state of diverse atmospheric aerosols. Their key factors, influencing the Earth’s climate, are atmospheric distribution, hygroscopicity, optical attributes and ability to interact with clouds. (Stocker et al., 2013, p. 602)(Stocker et al., 2013, p. 602)(Stocker et al., 2013, p. 602)(Stocker et al., 2013, p. 602)(Stocker et al., 2013, p. 602.) While interacting with clouds, their hygroscopic attributes are from highest interest since it is responsible for the liquid droplet formation. This effect is known as Cloud Condensation Nuclei (CCN) and is especially dominant when high aerosol concentrations interact with a cloud. Consequently, greater quantities of smaller water droplets are formed, leading to higher scattering of sunlight. Also precipitation is found to increase with high CCN processes according to latter research. (Fan et al., 2017; Jung et al., 2015)

Descriptive examples, of how high CNN concentration increases cloud precipitation is shown at Russian military parades at the celebration ceremony after the victory over the Nazis. Using the Airforce, they performed so called “cloud seeding”. Thereby, silver iodide is dispersed into the clouds that is acting as a condensation nucleus to form ice crystals with the given water vapor. After sufficient growths of the ice crystals, once the size of hail, they fall down towards the ground, whilst steadily heating up again and turning into rain. (Schmidt, 2017) Reports out of the Atmospheric Research journal show that effectiveness over cloud seeding is not quite established by meteorologists (Levin et al., 2010). The achieved effect is doubtful, especially regarding agricultural use to avoid strong hail precipitation but with concentrations of silver iodide high enough, effects are not disputed either since there are definite enhances for ice nucleation under the presence of silver iodide (Smith et al., 2019).

The exact effect of aerosols on clouds are difficult to estimate, since the mixture of different phases is especially sensitive to varying aerosols concentrations interfering with the cloud that is composed of altering ice and liquid water shares. However, most climate models claim that anthropogenic aerosol lead to a cooling effect on clouds. Typical CCN particles are sea salt, sulphates, nitrates and some organic origin. (Boucher et al., 2013, 623, 603)

As former mentioned, most atmospheric aerosols come in mixtures of both, organics and inorganics. King et al. (2010) and Prisle et al. (2010) have been further investigating the subsequent effect in the last decade. Not only can particles lead to increased condensation nuclei but also to intensified ice nucleation (IN), especially in high altitudes in which cirrus clouds opacity can be enhanced, thus radiation balances be affected (Fan et al., 2017). These ice phase processes are also thought to amplify precipitation amounts and onsets of the rainfall, especially for snow and ice build-up (Fan et al., 2017; Yang et al., 2020). Typical particles acting as ice IN are mineral dust, volcanic ash and bioaerosols. (Hoose and Möhler, 2012, 9819 et sqq.)

Whereas the ability of mineral dust and volcanic ash does not seem to be in question, the impact of bioaerosols is thought to be lower due to less concentration in the atmosphere (Sesartic et al., 2012, p. 8646). The effect that soot and the correlated black carbon particles have on ice nucleation are uncertain. On the one hand are reports claiming, that BC does not act as an ice nucleus (Dymarska et al., 2006; Friedman et al., 2011; Kanji and Abbatt, 2006) and on the other hand there are many stating the opposite (Fornea et al., 2009; Kireeva et al., 2009; Popovicheva et al., 2008). However, considering their measurement models there seems to be a relation regarding present atmospheric temperatures, in which BC sometimes acts as an IN and other times not.

All the above-mentioned climate models underlie the uncertainties of unknown wet distribution of aerosols. This is, for the most part, relevant for the radiative forcing and optical properties. (Emanuelsson et al., 2013; Xu et al., 2019; Yoon and Kim, 2006) Since the atmospheric humidity is a globally high fluctuating variable, the particle behaviours and measurements techniques are swayed heavily. The impacts of varying humidity on measurement practices have been shown by multiple scientists. (Cai et al., 2014; Düsing et al., 2019; Nessler et al., 2006) These reports are elevating the role of humidity for the outcome of following meteorological processes. The following Figure 3 describes the interaction of atmospheric aerosols, greenhouse gases along with cloud precipitation and the occurring radiative forcing on the global surface temperature that have been described above.

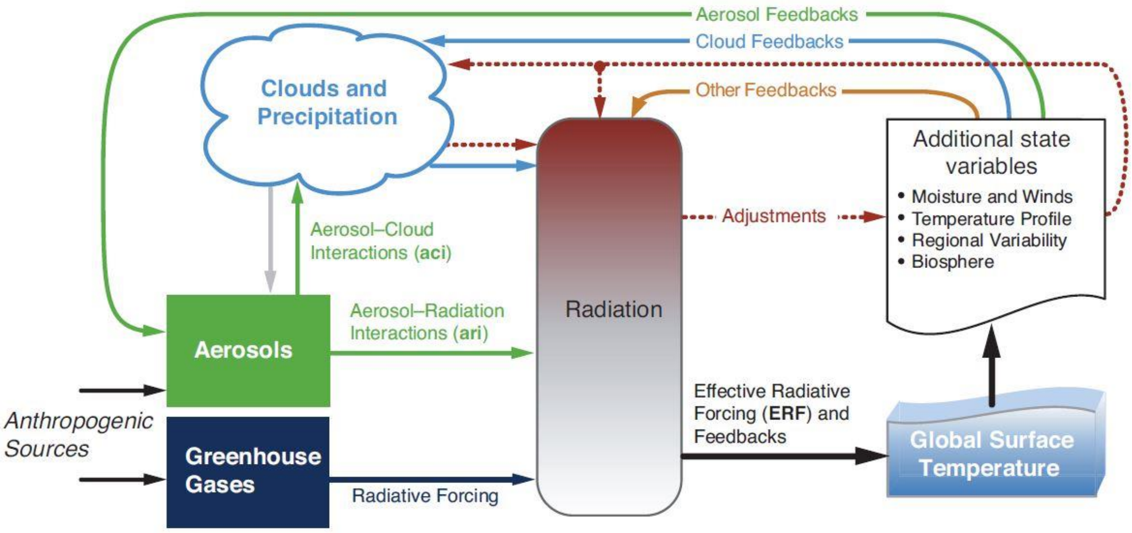

Figure 3: Overview of radiation drivers in our atmosphere and feeback inference of aerosols, greenhouse gases and clouds (Boucher et al., 2013, p. 577; Stocker et al., 2013, p. 577)

Represented is how the driving anthropogenic operators (green and dark blue) apply actions on the radiative forcing. The radiation is underlying influences of adjustments (red) that are affecting the present state variables and those again affecting everyone else. Whilst clouds and their precipitation are correlating with aerosols, they are also influencing the radiation by their cloud albedo effect. Conclusively, the radiation leads to an increase in the global surface temperature.

2.4 Aerosol Measurement Techniques

The Earth's climate and air quality is largely dependent on aerosols. Continuous and sufficient measuring allows us to make qualitative statements about these two concerns. The measurements must be reliable thus it is essential to check them for any error sources. A continuous development process of measurement methods is important and requisite in order to achieve high-quality, meaningful results. In an effort to be able to draw not only regional but also global conclusions for the world climate and the particle composition in the air, measurements must be taken ubiquitously and meaningful results must be obtained by quantitative alignments of measured values within an environment. Information about multi-decadal time scales will allow us to predict trends occurring in our atmosphere and consequently enables us to adapt to these conditions and learn about the most relevant aerosol variables that need to be measured globally. The first IPCC reports about serious concerns regarding climate change have been made in 1992, advising observation departments all over the globe to track the current changes in global surface temperature increase and ocean level rise to further understand the atmospheric drivers affecting this exceptional rapid changes in the last 100 years. (IPCC, 1992)

Since then, the maintenance and capacities of observation stations have been enhanced to improve monitoring of climate trends. After 1990 most near-surface aerosol concentrations in the aeras of Northern Europe, Northern America, and the Pacific Ocean show decreasing levels. Complementary, the regions of Antarctica, eastern and southern Asia show increasing levels. The reason for the Antarctic region mainly being the heavy construction in the last decades and the low number of observation stations in Asia and the tropics are leading to low confidence in their trend analyses. (Asmi et al., 2013; Collaud Coen et al., 2013; WMO/GAW, 2016)

Fortunately, the range of diverse measurement instruments and strategies is extensive. Together they dominate the measurement approach that will be taken. Aerosol properties like size distribution, retention periods, physical and chemical characteristics, hazard potential and location of occurrence reduce the margin of possible techniques immensely. Also, the inquirer of the measurement narrows the instrumentation feasibilities by determining the desired accuracy, precision, portability, instrument size, dynamic range, time resolution and any other potential resource constraints. (Kulkarni et al., 2011, 55 et. sqq)

Each sampling system only offers a limited amount of capabilities but ideally it should at least feature the following characteristics. Any kind of precipitation from either sampling in direct rainfall or being immersed in a cloud, should not affect the sample. Depending on the aerosol properties it should minimize losses that are due to diffusion or inertia of the particles while being sampled to produce a representative ambient aerosol probe. Further, a humidity control is needed to make sure the sampled particles do not grow from nucleation because of hygroscopic effects. Desirable relative humidity should be below $40\ \%$, this can be achieved by the help of impactors and cyclones or by heating the instrument sampling tubes. Thereby, temperatures above $40\ °C$ should be avoided to ensure semi-volatile particles are not disappearing. Holding a steady warm temperature also avoids any ice build-up near or inside of the inlets. Lastly, the evaporation of volatile particulate matter should be minimized. Combining these features most of the aerosol measuring instruments have an inlet, sampling the aerosol, on the outside of the set-up. Following, the sampled aerosol is being transferred through smooth pipes and tubes and face a conditioner that is drying the flow when finally, a splitter is allocating the aerosol particles into their varying sizes and different technical components within such a system. Self-evidently, the measured particles or even the whole instrumentation should be stored in environments that provides ordinary temperatures, avoiding any kind of peaks towards extreme heat or cold and a general clean environment. (WMO/GAW, 2016, p. 6)

Most unwanted ambient conditions can be avoided by using a vertical duct with a cover that is holding back drizzle, rain and various winds speeds and directions from entering the inlet. The vast majority of measurement institutions recommend an upper cut of point at $10\ \mu m$ to exclude any larger particles from sampling since they are not representative for regional scale aerosols and their impact on the Earth’s climate. Particles of that size are undergoing immense effects of gravitation and therefore fall quickly to the ground, resembling particles of rather local origin. Further aerodynamic size cut-offs of $2.5\ \mu m$ in ambient conditions and $1\ \mu m$ at dry conditions are advised to distinguish fine and coarse particles. (Aerosol, Clouds, and Trace gases Research InfraStructure Network, 2011; WMO/GAW, 2016) While the air flow within the sampling tubes is responsible for the particle motion and reflects the accuracy and precision of the measurement, there are two mathematical equations that are from higher interest.

The Reynolds Number, in short Re, describes the state of an air flow in a pipe and shows whether it is laminar or turbulent. Approximately a Reynolds Number of 2000 resembles the breaking point between a laminar flow, below that number and a turbulent one, above.

$$Re_{flow} = \frac{\rho_G \cdot u_{flow} \cdot d_{pipe}}{\eta_G} \quad (1)$$

In this connection ρ_G stands for the gas density, u_{flow} for the flow velocity, d_{pipe} for the inner diameter of the sampling pipe and η_G for the gas viscosity.

Secondly, the Stokes Number characterizes the inertia of a particle in such a sampling flow.

$$Stk = \frac{\tau \cdot u_{flow}}{d_{pipe}} \quad (2)$$

with

$$\tau = \frac{\rho_p \cdot {d_p}^2 \cdot C_C}{18 \cdot \eta_G} \quad (3)$$

Hereby is τ the relaxation time of the particle of interest, u_{flow} the flow velocity, d_{pipe} the inner diameter of the sampling pipe, $\eta_G$the viscosity of the gas, ρ_p the particle density and C_C the Cunningham correction factor. (WMO/GAW, 2016, pp. 9–10)

2.4.1 *In situ* measurement

The in-situ measurement approach reflects a near real time measurement of either substrate-based collected particles or individual airborne particles. Its advantages of being quick are confronted with the characteristic of being expensive and occasionally limited in times of possible variety of direct particle analysis. Further, this type of measurement can be sub-divided into extractive and external sensing technique. Being an external, non-invasive measurement, it allows to handle the aerosol in its undisturbed native state. Regarding hostile environments, like extreme pressure or temperature this can be an advantage over the

extractive measurements that require the aerosol to be brought to the instrument sensor. (Kulkarni et al., 2011, 10, 295)
The easiest and quickest approach to extractive substrate-based collected particle mass measuring is to deposit the particles on a vibration surface and examine changes in the resonant frequency. Hinds (1999, p. 144) has described this technique extensively. Another option for this measuring method is the use of ß-radiation scattering. By analysing the attenuation of radiation reaching the detector an approximate, proportional to the attenuation, mass of the material can be found. It is to be mentioned that this technique does not work for low atomic number elements, like hydrogen (^{1}H), since there are not enough protons inside of the element for the radiation to reflect from and thus risking a possible under detection. (Kulkarni et al., 2011, 58 et sqq.)

To detect and measure individual airborne particles, spectrometers are required to observe particles quickly and efficiently. Spectrometers account to the extractive real time measurement techniques and use either light or laser sources to create a sensing zone for the particles to pass through. An optical particle counter (OPC) is a commonly used system that in case of using a laser is also widely known as a laser particle counter (LPC). LPCs are relatively inexpensive and have the advantages of being non-destructive and able to detect particles at a high speed. The light scattering by each particle in the sensing zone is detected and converted to an electronic pulse that is revealing the particle size. Thereby, the sensing volume does not have to be within the instrument, thus enabling the measurement in exceptional environments, for example, in extreme heat, cold or wind speeds.

The disadvantage of OPCs is the sensitivity loss in the small particle range. Particles below $50\ nm$ of diameter are not being detected with high reliability. In these cases, condensation particle counter (CPC) or also known as condensation nucleus counter (CNC) are used. They use a supersaturated environment and the characteristic of most particles being hygroscopic to let vapor condense onto them. Consequently, the particles grow approximately the same size and can then be detected by light scattering systems again. CPCs can detect particles as far as down to $1\ nm$ in diameter. Overall, spectrometers are famous for their ability to detect size distributions and concentrations over a wide range.

Lastly, electrometers can be used for extractive near real time measurement. Still being an extractive system, it measures aerosol particle charges. The induced electrical current originates from a Faraday cage that only works if sufficient flow rate of charged particles passes through a particle filter inside of it. Since the induced current is too small it needs to be amplified and followingly can be measured by electrometers. This system is prone to a few circumstances, as the particle charge distribution, flow rate and electrometer characteristics all affect the accuracy. A system that allows external particle measurement is the forward-scattering spectrometer probe (FSSP). This way, the process is non-invasive and allows to observe extreme ambient environmental conditions as well. This spectrometer is operating in a similar way as the former ones but can be mounted on aircrafts to gather atmospheric data at speed up to $125\ m/s$, allowing extensive atmospheric aerosol studies. (Kulkarni et al., 2011, 59, 299 et sqq.)

2.4.2 Collection with subsequently laboratory analysis

By this approach filters are commonly involved in the process and often present efficiencies, in collecting particles over the whole size range, up to $100\ \%$. A further classification in sampling devices can be achieved into multiple size ranges using inertial separation. Cyclones and impactors are commonly used to do so. Cyclones use circulation of air to separate larger particles due to centrifugal forces and impactors use an abrupt change of the airflow direction by leading the air stream around sharp angles in the channels. That way the larger particles get separated by their inertia. (Kulkarni et al., 2011, pp. 57–58)

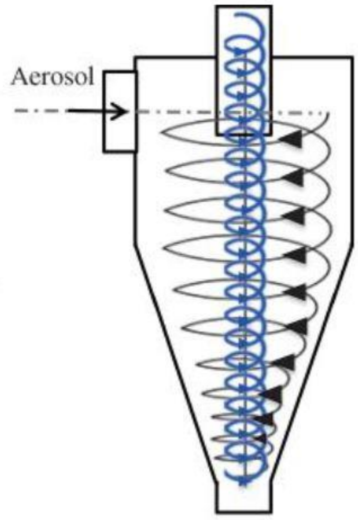

Figure 4: Simplified display of a single-stage cyclone (Colbeck, 2014, p. 64)

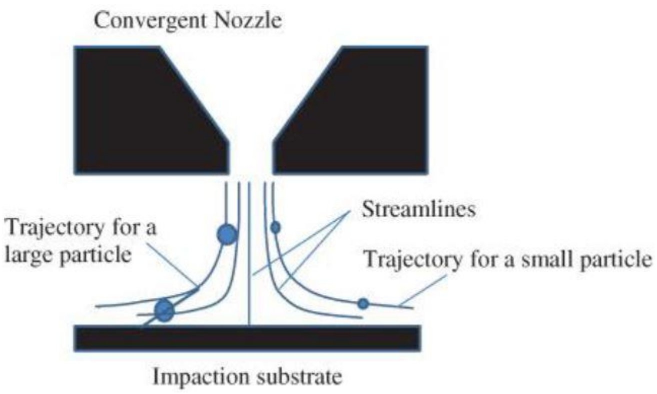

Figure 5: Simplified display of a single-stage impactor (Colbeck, 2014, p. 64)

These two systems are used to measure respirable aerosols. Respirable aerosols are particle in the size range of fine and ultrafine sections, being $0.01 - 10\ \mu m$ that are able to penetrate the tissue inside of the lung, possibly causing health problems. (Baron, 2014, p. 3; Kulkarni et al., 2011, p. 45) Cyclones and impactors are commonly used in front of filters to simulate the removal of particles by the upper respiratory system. That way, only particles that can possible reach the alveolar or other sensitive areas of the lungs get into the filter. The sample on the filter can then be analysed by gravimetric, chemical, radioactive, biological, microscopic and spectroscopic approaches. Particle size separation and classification can be achieved by various types of classifiers that get installed in series such as a cascade-system. The cascade works as a step by step classifier, collecting particles at each stage that are larger than those in the subsequent stages. Following, the quantities of collected particles at each cascade stage can give insides of the overall investigated particle distribution. If particles below $1\ \mu m$ want to be classified, so called diffusion batteries are being used. These batteries have bundled plates with holes that enable the particles to diffuse to the surface on the other side of it. The collected particles, once diffused through the plates, can then be analysed for their characteristics of interest. On the one side being rather inexpensive it only has a limited size resolution, smaller to the ones of impactors. (Kulkarni et al., 2011, pp. 57–59)

2.4.3 Measurement Errors

While sampling aerosols with instruments already bares many potential measurement errors the sampling inlet configuration is the first sensitive part of the instrument creating a likely error source. After entering the sampling inlet, differences in the particle flow velocity and turbulences occur. Thereby, the shape, size and orientation in which the inlet is mounted on top of the meter affects the sampling efficiency. (Kulkarni et al., 2011; Liu, 2013) Also, the weather or any kind of variable that might be occurring, because the meter is too close to ground, like kicked up dust or surface turbulence due to enhanced friction between the wind and the surface near to the ground, might affect the measurement process. Because of that, the WMO recommends a minimum measurement height of $2\ m$ above the ground level. (WMO/GAW, 2016, p. 15)

After the intake of the probe through the inlet, it has to be transported to the collection filter via tubes and channels. Electrostatic attraction impaction or gravitational settling, especially in the upper particle size range, will lead to losses. Below $1\ \mu m$ of particle diameter also diffusion processes in small inlet devices affect the deprivation of the measurement efficiency. That is why tubes and channels, responsible for the transportation of the sample, must be made from conductive materials to lower electrostatic attraction. Further, electrical grounding and reduction in length to minimize impaction or gravitational losses benefit the efficiency. This sedimentation effect is especially present in sloping or multiple bended transport tubes. Avoiding sources that could cause turbulences within the transport system, like bends, tube connectors and keeping the sampling lines as short as possible, will help with minimizing efficiency losses greatly as well. (Kulkarni et al., 2011, p. 61; Liu, 2013, p. 37; WMO/GAW, 2016, p. 17) Generally, the inlet efficiency is highest when the airflow velocity and direction in the sampler and surrounding area are exact or nearly the same.

If the temperature spread between the local dewpoint and the ambient air temperature in the measurement environment are too far apart, a sample drying is advised. At room temperature the relative humidity will always be below $40\ \%$ inside of the sampling tubes and channels. Below that percentage the hygroscopic growth is known to be less than $10\ \%$ of the original particle diameter and therefore negligible. If the relative humidity is higher than that, sample dryers can be used. Dryers made out of elastic tubes based on vapor-permeable membranes, water absorbing silica gels or heating systems are keeping the relative humidity below $40\ \%$ in the sampling lines if necessary. (Colbeck, 2014, pp. 49–53)

After the particles way through the inlet they are collected on a filter. Once on the filter, they can be further analysed by sensors or detectors. Optical microscopy detectors have the disadvantage of not being able to detect particles smaller than about $0.3\ \mu m$ and thus hold a reasonable contingent of bias. But not only optical microscopy detectors have such bias, in fact, all kinds of detectors and sensors, especially in the real time measurement techniques have such systematic efficiency losses varying in magnitude depending on their capabilities of measuring different particle size ranges and ambient variables. (Kulkarni et al., 2011, p. 61)

Since most detectors have larger bias in the small particle size range, this error is especially significant when measuring high concentrations of small particles. Together with the losses that occur at the instrument inlet they modify the particle distribution, revealing a smaller particle range measured than actually present. The following Figure 6 graphically visualizes the effect of bias due to detector sensitivity and inlet losses.

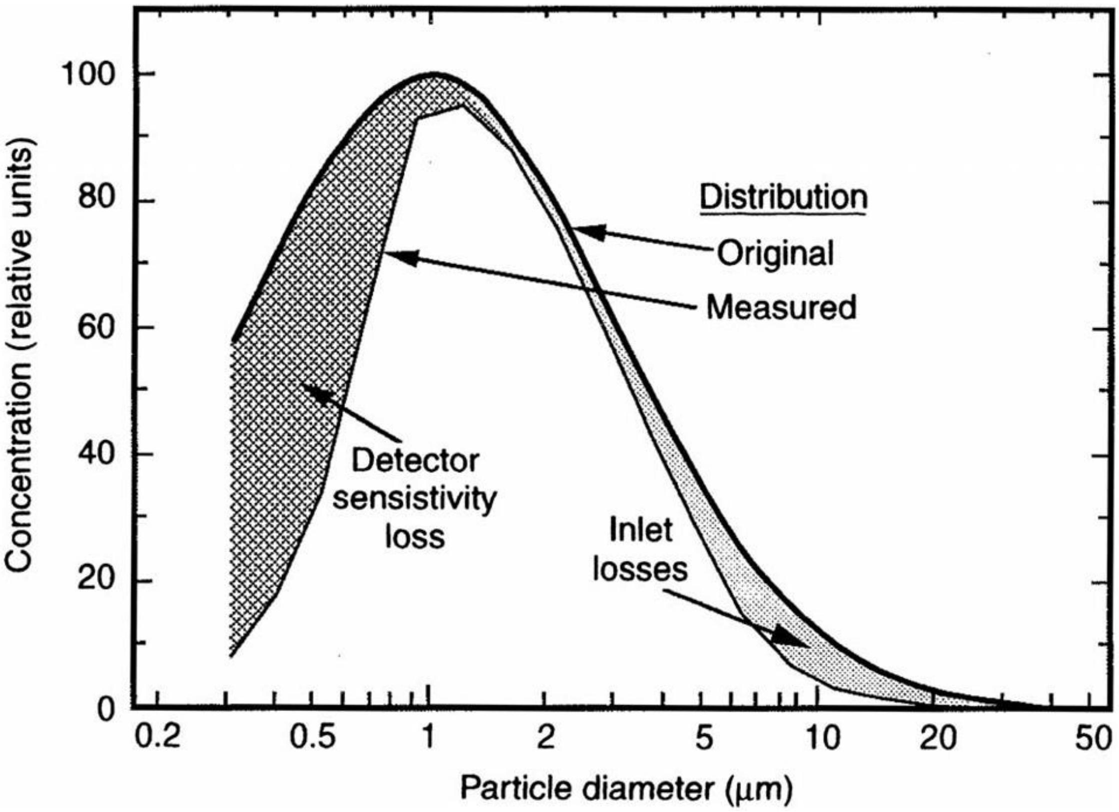

Figure 6: Particle detection bias for a aerodynmaic particle sizer (Kulkarni et al., 2011, p. 62)

Equally important are the influences of coincidence error in detectors. Optical detectors that rely on light scattering techniques detect a signal each time a particle passes through the sensing zone. Coincidentally, there might be a presence of multiple particles within the sensing zone. If not properly detected by the laser, this will lead to erroneous perceptions, either by overestimation of particle size or underestimation of particle count, since two individual particles potentially get analysed as one larger particle. (Kulkarni et al., 2011, p. 62)

Additionally, aerodynamic particle sizer (APS) are using laser Doppler detection systems, invented by Wilson and Liu (1980). The system measures the time of an, by a nozzle, accelerated particle between two laser beams that are positioning within a known distance at the beginning and end of the sensing zone. If by coincidence a particle hits the first laser before the previous particle hitting the first one, passes laser two, a so-called “phantom count” is being detected. This leads to additional errors in the mass, size and number distribution, especially at the tails and minima of measured distributions since they show increased sensitivity to minor fluctuations. (Heitbrink et al., 1991, p. 123.) Moreover, failures are greater at high concentrations. The following Figure 7 envisions this scenario.

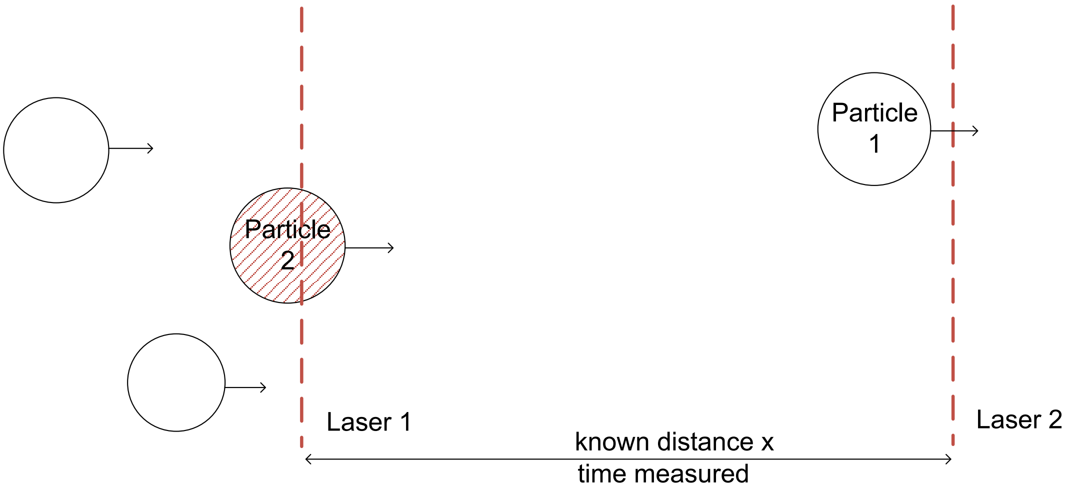

Figure 7: Visualization of phantom count due to the presence of more than one particle in the sensing zone (Own Creation)

Since diverse measurement instruments are depending on particle size, attributes and properties, they will have differing results. Conclusively, Figure 8 demonstrates how five different measurement techniques have significant varying results, regarding their measured particle distribution because of bias and coincidence errors.

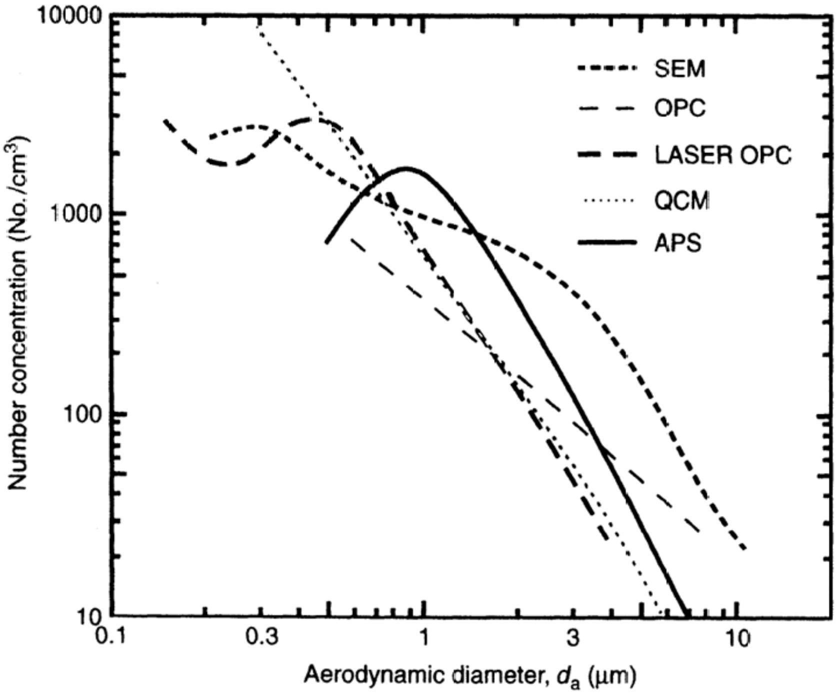

Figure 8: Differing measurement results of 5 measurement techniques due to bias and coincidence errors (Kulkarni et al., 2011, p. 62)

All these above explained error sources must be compensated using appropriate correction factors to guarantee reliable and accurate results. If multiple instruments and techniques are involved in the particle measurement process, correction factors for non-matching equivalent diameters must be taken. Additional errors are also present when the conversion of different equivalent diameter types is not adequately corrected. (Colbeck, 2014; Kulkarni et al., 2011, pp. 55–65; Liu, 2013)

In all measurement cases the standard deviation is commonly used to express the amount of scattering of an assemblage of measured values. Mathematically it is defined by the square root of the total number count.

$$\sigma = \sqrt{N} \tag{4}$$

Hereby N stands for the total number count. Consequently, to achieve an uncertainty of $1\ \%$ you will need to sample 10000 particles as the following equation shows.

$$\sigma = \sqrt{10000} = 100$$

and

$$\text{Uncertainty}\ x = \frac{100}{10000} = 0.01 = 1\ \%$$

This demonstrates the importance of measuring large enough samples within a population of particles to achieve low enough uncertainties. (Bland and Altman, 1996)

2.4.4 Remote sensing

The vertical aerosol concentration in our atmosphere is defined by the aerosol optical depth (AOD). The measurement of AOD is used to collect insights on the solar radiation scattering and absorbing by aerosols in our atmosphere due to their albedo effect. Either ground-based remote measurements or satellites are used to collect the AOD data that nowadays represents a valuable source of information for the health and air quality departments. (Fiore et al., 2018)

Generally, the AOD data received from the ground-based stations is more accurate due to the absence of surface reflectance issues. The most known ground-based station is the Aerosol Robotic Network (AERONET) which uses radiometers and sun photometers to measure the direct spectral transmission of solar radiation through our atmosphere. With a known solar irradiance at the top of our atmosphere, a known air mass in our atmosphere, the total optical depth is defined. The total optical depth derives from the various scattering and absorption processes by gaseous molecules, aerosols and some trace gases. Knowing the total albedo contribution by components other than aerosols, its value can be deducted from the total optical depth, revealing the AOD. (Colbeck, 2014, pp. 120–121)

2.5 Implementation of drones

Numerous studies from the previous chapters have shown that aerosols have a significant influence on the Earth's climate and the radiation budget of the Earth. So far, ground- and satellite-based technologies have been used to obtain information about the aerosol distribution in our atmosphere. Particle measurement devices have also been attached to manned aircraft to obtain regular and accurate in-situ results of aerosol distributions. However, the use of satellites and manned aircraft is subject to significant financial and legal limitations. These are reflected in airspace restrictions, noise restrictions, emission limits, bad weather conditions and more.

In addition, many sources of high particle concentrations are relatively low to the ground, posing an increased risk for manned aircraft particle measurement. Unmanned aerial vehicles or systems, also known as UAVs and UASs, therefore have great advantages and enable particle measurement in locations and areas that are not accessible to manned systems or balloons. UAVs can cover large areas and excess remote or dangerous locations and resemble a more flexible solution. They can be divided into four main types: fixed wing, rotary wind, blimps and flapping wing UAV. The biggest advantages are thought to be with the rotary wing UAV, also called vertical take-off and landing (VTOL), because they obtain great hovering capabilities and exceptional manoeuvrability. (Luo et al., 2016, p. 124)

The outcome of the measurement accuracy, measurable size range and sensitivity is dependent on the airframe dimensions and carriable weight of the UAV as well as its general shape, since they affect the possibilities of mounting instruments of varying sizes and weights on it. Moreover, the achievable flight time, is a factor strongly affecting the measurement possibilities. Some remote places might be too far away in horizontal or even vertical dimensions to be reached in time before the flight endurance of the UAV depletes. But as the technological progress is constantly improving the efficiency of storage batteries, they become a challenge that stands a good chance of improving in sufficient ways.

2.5.1 Former implementation of drones

In the last decade, the common implementation of unmanned drones in our life has become increasingly usual. There are various research teams exploring the capabilities of particle measurement instruments mounted on drones. So far, vertical heights of approximately $2.5\ km$ have been achieved and gathering relevant weather data, like wind velocity and direction, humidity and temperature has become a standard procedure, at least for the lower atmosphere. Most times, OPCs have been found to be the best choice for regional air particle distribution measurements in our atmosphere. (Ahn, 2019; Bieber et al., 2020; Chiliński et al., 2018; Heesang et al., 2018; Mamali et al., 2017; Villa et al., 2016)

The relevance of reliable and accurate air particle measurement in our atmosphere and their impact on Earth’s climate and radiation capabilities have been extensively discussed in the previous chapters. Moreover, drones have been used to explore hazardous areas like active volcanoes in Central America. That way, it is possible to obtain insights about the current particle deployment of active volcanoes and possibly gain information about their activity. The measured data gets compared with the data detected at the ground-based stations to insure its reliability. (Stix et al., 2018)

The localization of gas sources has been a value adding possibility for drones. Discovering leakages early on with unmanned vehicles has promising potential to improve risk management of people living close to them or manned vehicles that need to get close enough to the gas source in order to track it properly. Further, it allows the mapping of volatile gases. (Neumann et al., 2012; Neumann et al., 2013; Rossi et al., 2014)

Drones offer a great solution for air pollution measurements of traffic, power plants, urban and industrial areas that are commonly sources of high particle emissions (Toscano et al., 2011; Villa et al., 2016). Also, ships have exceptional high BC emissions and spread those over maritime areas in which they get dispersed by wind and vertical air movements (Buffaloe et al., 2013; Corbett et al., 2010; Lack and Corbett, 2012). Measuring in those areas by the help of UAVs has been a new possibility to create such air pollution analysis, since former estimations have been made by remote sensing systems that could not deliver real in-situ results (Corrigan et al., 2008).

2.5.2 Possibilities of drone usage in the future

Combining image processing software and high-quality cameras with drones allows to perform exceptional mapping potential. Jellyfish, for example, represent a group of organisms that play an important role for the maritime biomass balance and have a key role in the maritime ecology systems (Fleming et al., 2015; Stoner and Layman, 2015). Further, there has been an international increase in demand for edible jellyfish products, which highlights the need of an efficient jellyfish monitoring system. Common observation techniques have not been ideal for this process that is why the implementation of UAVs is now investigated. So far, tests have shown that camera equipped drones offer the possibility of daily maritime biomass monitoring over large areas with satisfactory efficiencies. (Raoult and Gaston, 2018)

Since drones already have the capability to monitor organism in the water, it could open up the opportunity to measure the air particle concentrations in areas of high quantities of certain organisms to discover any alignments between their presence and particles that they emit. It is known that every organism is also the source of some emissions. If these get distributed with the air that is above the water, it could be possible to conclude extraordinary presence of the emitting organisms in the surrounding area of measurement to unusual high particle concentrations of a certain kind. By that, the knowledge about the diversity of different organisms and especially their quantities will be quicker and easier to obtain and following actions can be made.

Perhaps more important as for the first quarter of the year 2020, the use of drones in case of pandemics, such as the Wuhan SARS-CoV-2 crisis, have proofed to be from irreplaceable aid. The term “social distancing” has become a matter to be dealt with by nearly everyone in the world in the year 2020. But these special times demands people to spend substantial times outside with others, while extensive shopping to save up supplies for a certain period of quarantine, collecting medical supplies for the personal health management or going to hospitals in case of indicating possible symptoms of the virus infection. For these scenarios, drone implementations have been helpful. They deliver supplies in areas stricken by the virus and reduce delivery times up to $50\ \%$ compared to road transportations, due to their high speeds of $27-45\ \frac{m}{s}$ without any care for traffic. (Flynt, 2018; Skorup and Haaland, 2020) Moreover, no humans are involved in this process leading to decreasing infection risks and highly human resource availabilities at areas where they are needed.

The medial supply delivery has been especially useful for hospitals that are in need for immense quantities in these times (Jingli, 2020). Equally important is the virus probe delivery to laboratories for quick analysis and following diagnosis. Not only hospitals, but also local testing stations are showing benefits from this. In the origin of this pandemic in China, they implemented drones with thermal imaging software to detect pedestrians that could possibly have the virus infection due to increased skin surface temperatures (Jakhar, 2020).

Lastly, grocery shopping and the providing of any other supply would be enormously beneficial by using drones, especially for rural areas (Skorup and Haaland, 2020). Now to conclude these existing possibilities with future implementation of drones regarding the aid of pandemics, a virus or bacteria measuring UAV could gather data of their presence and by mapping, reveal areas of increased infection risks. This would benefit the planning of logistic transport and inform pedestrians of potential hazardous places that they should avoid in order to decrease the infection risk. Adding to this scenario, drones could be used to test potential infected people in the first hand, by analysing breath or cough samples without the need of any participation by medical professionals, thus relieving healthcare capacities.

Refineries and other chemical processing facilities require control leak detections and regular inspections. As described in the previous chapter, UAVs are already able to detect gas leakages when equipped with the adequate instrumentation. Transferring this ability to the large scale by quickly covering large areas with the needed measurement system to detect such leakages, represents a valuable opportunity for the implementation of drones in the industry. (Rodriguez et al., 2017)

Furthermore, airplane accidents because of unaware entering of high particle clusters in the atmosphere, like volcanic ash clouds, have been a serious threat for the aviation industry. 1982 a British-Airways Flight, known as the Jakarta incident, unknowingly entered a cloud of volcanic ash from the eruption of Mount Galunggung. Consequently, all four engines failed but were able to be restarted once a long glide has been made. (Tootell, 1985) By monitoring areas of high interest, for instance the Ring of Fire and locations that are known to be in the immediate affected area of active volcanoes, on unusual high concentrations of volcanic emissions, these kinds of incidents could be prevented in the future.

1986 was the year of the radioactive catastrophe in Chernobyl. One of the first countries that noticed a potential accident and was heavily affected by its consequences, was Sweden. (Moberg, 1991; Persson, 1987) That is because of the long-distance transport if radionuclide that are suspended in the atmosphere by the weather movement. A regular or perhaps continuous surveillance of radionuclide deposition in the area of active nuclear power stations by drones, could accelerate of noticing of such accidents and therefore help to minimize damage to the environment and humans.

3 EMPIRICAL FRAMEWORK

Because of the current SARS-CoV-2 pandemic, no empirical testing could have been made by this stage of the thesis. To open up the opportunity for later investigations regarding the mobile measurement of aerosols with drones, the planned tests will be explained in the following chapters. It is to be mentioned that the described tests do not cover every potential erroneous scenario of the drone implementation while measuring and thus can be extended or modified.

3.1 Hand-held vs. airborne testing

This test serves the purpose of revealing any kind of occurring measurement deviations between a hand-held measurement using the sampling instrument and an airborne testing, by which the meter is mounted above or under the drone. The results of this test could already give a rough estimation of where to mount the meter on the drone, depending on the measurement deviations received above and under the drone. If the variation of the measured values is within an inacceptable range, further testing increases in relevance. If the results are approximately compliant, it still does not take the need for additional testing. Because in any case, this test does not consider a variety of potential disturbing influences, hence more tests will have to be made to guarantee reliable measurement results with sufficient confidence.

3.2 Minimum required vertical distance to ground

To produce lift, the rotors of a drone spin at high rotational speeds. The geometric design of the rotor blades cause a rotating downward orientated air flow. If the vertical distance between the rotor blades and the surface is not adequate, particles, primarily being dust particles, will be whirled up. The minimum required height depends on the strength of the thrust generated by the drone. Since the drone does not only have to carry its own weight, but also the mandatory instrumentation, the thrust will have to be increased compared to individual drone flights. Furthermore, the characteristic of the potentially whirled up particles is affecting the required height as well. Coarse particles will be possibly stirred but due to their relatively high gravitational settling the risk of distorting the measurement is rather low. However, fine and ultrafine particles will be whirled up more easily and could affect the particle distribution in the measurement environment.

Since particles are displacing each other, too short distances within neighboured particles could educe a chain reaction by the whirled-up particles. Therefore, the minimum required vertical distance h_{min} will be needed to investigate. Figure 9 describes the experimental set-up to perform this test.

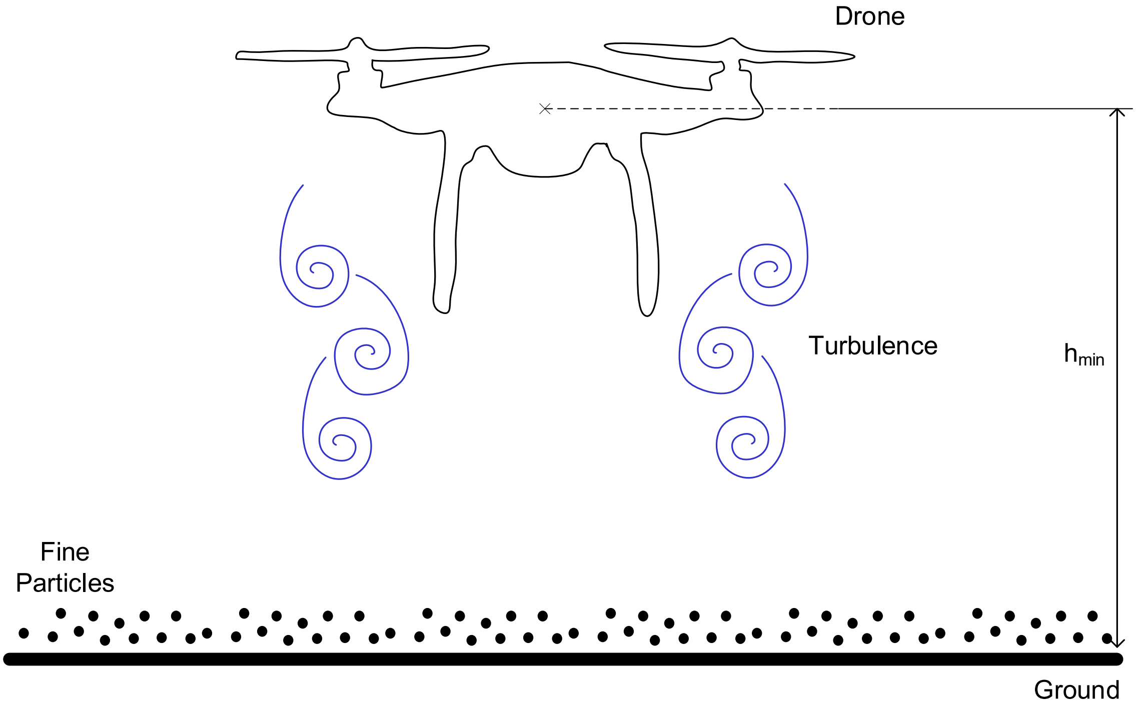

Figure 9: Experimental set-up for investigation of the minimum required vertical distance (Own Creation)

If the measurement results of the meter that is mounted on the drone, do not show any significant measurement deviations while hovering at a certain height, the current height above the ground is satisfactory.

This test could be executed by incrementally decreasing the vertical distance h to the ground. To guarantee a successful investigation the test should start at a height from which no particles are whirled at all. Furthermore, to not only inspect the measurement deviations of the meter but also any potential particle movement as a result of the drone rotor turbulences, the particle visibility could be enhanced. This allows for visual assessment by preparing particles of various sizes, weights and associated colours that can be spread on the ground surface. It should be considered that fine and ultrafine particles are not properly visible even if they are coloured, therefore measurement meter deviations are still to be analysed. Depending on the desired measurement accuracy the incremental descending steps can be adjusted. Thereby, it is also reliant on the height controllability of the drone controller. However, steps of approximately $5\,cm$ should achieve satisfactory results.

3.3 Visualization of effective turbulent area beneath rotors

Given a theoretical motionless homogeneous concentration of air particles, the main factors of possible distortion can be diffusion with surrounding particles and the influence of turbulence. In both cases, the initial homogeneous particle cluster will be changed in size and presumably in its shape as well. (Thorpe, 2009, p. 367) The following Figure 10 shows the effect of diffusion and turbulence to such a concentration of particles.

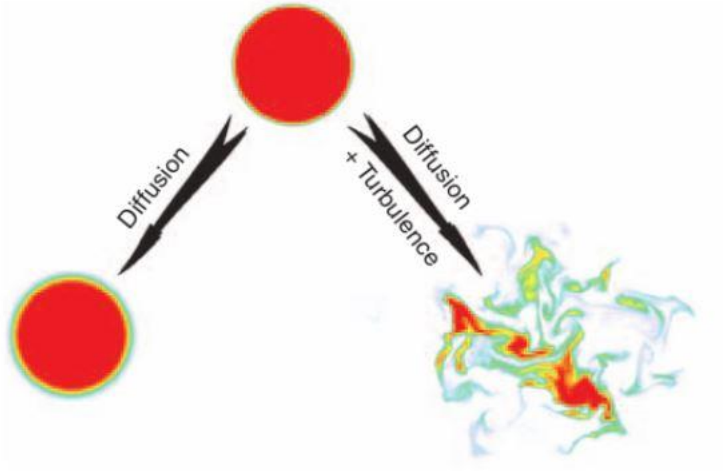

Figure 10: Visulazitation of the effect that molecular diffusion and turbulence can have on particle clusters (Thorpe, 2009, p. 367)

The initial state is demonstrated at the top of the Figure 10. The colours define the concentration gradients being present within the particle cluster. Red stands for a high concentration and yellow, green and grey each symbolize a less strong gradient than the previous one. A circular homogeneous particle concentration under the effects of diffusion with other particles is shown on the bottom left. The circular region is still motionless, just slightly increased in volume. On the lower right side, the results of mixed diffusion and turbulence effects are shown. There are no smooth concentration gradients left and the cluster has been distorted into an irregular shape.

The rotating blades of the drone are known to leave behind a wake turbulence, also known as vortex wake area, underneath its origin. NASA used their high-fidelity Computational Fluid Dynamics (CFD) simulations on supercomputers to investigate the complex physics of rotor turbulences deployed by drones. (Ventura Diaz, 2018)

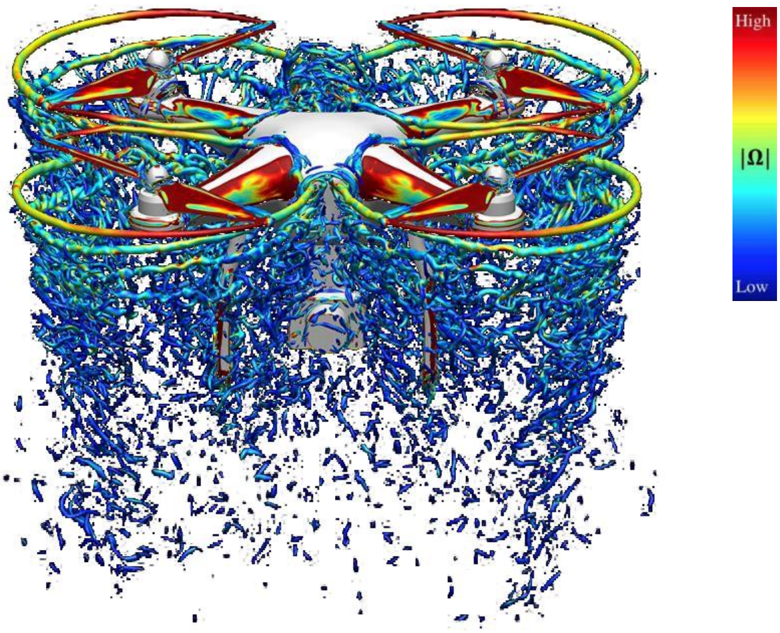

Figure 11: Visualization of the air flow of NASA's DJI Phantom 3 quadcopter while hovering (Ventura Diaz, 2018)

The vortex wake area is coloured by its vorticity strength Ω. The vorticity describes the magnitude of turbulence in a certain area. Red defines locations of high vorticity and blue symbolizes low amounts. Adding to various CFD simulations that try to analyse the turbulent area beneath drone rotors, a practical in-situ test could reveal helpful visualizations about the behaviour and extent of the vortex wake area.

This test tries to investigate the extent of the produced turbulence area by identifying the length of negatively affected area underneath the drone rotors. Through attaching wool strings on a holding ring that is connected to a rigid tube underneath a drone rotor, rotating with the required rotational speed in order to hover at a certain height while carrying the drone with the desired instrumentation, the effect of the vortex area can be visualized. Extending the length of the rigid tube, as shown at the Figure 12 below, allows to increase the distance between the signalizing wool strings and the drone rotor. If the wool strings are moving rapidly, it shows that they are within the vortex area. Once, a certain distance between the wool strings and the drone rotor is achieved, the wool strings will stop to move due to the sufficient distance from the generated turbulence. This is the minimum needed distance for the measurement instrumentation to not be affected by any kind of turbulence.

Again, incrementally increasing the length of the rigid tube will allow for precise analysis to determine the mandatory distance from underneath the drone rotors. The incremental steps should correlate to the desired measurement accuracy. Thereby, finer steps will achieve higher accuracy of the gathered results.

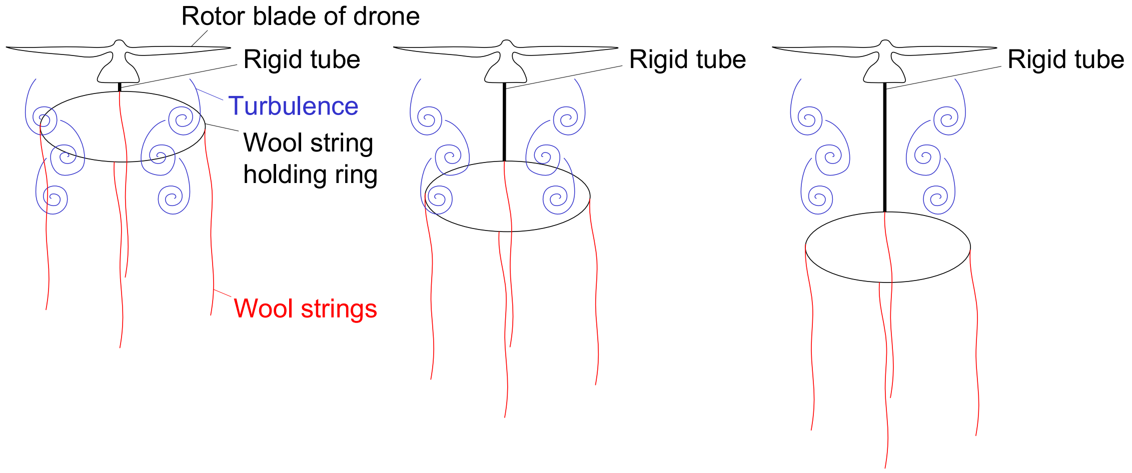

Figure 12: Experimental set-up for the potential vortex area visualization test (Own Creation)

3.4 Measurement reliability in turbulent conditions

The last planned test tries to identify any complications occurring with measuring while being exposed to turbulences. Even if the abilities of the measurement instrument implement a pump to suck in a defined volume of air, the characteristic of that probe could vary in different wind flow conditions. A turbulent air in the immediate surrounding of the instrument inlet could have similar effects as a cyclone classifier. That is, because the turbulences will potentially have the ability to cause a rotational motion on the air flow that is being sampled by the inlet. In the rotation of the air flow, the particle's mass is dominating the extent of centrifugal forcing, possibly causing a separation of particles with varying masses. Within a particle cluster of similar kind, the size determines the mass of the particle and hence the measured particle size range could be erroneous. The following Figure 13 and Figure 14 display a realisation of this test.

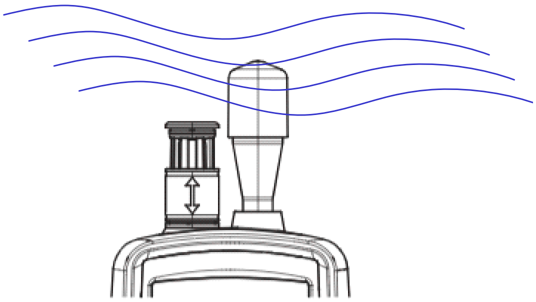

Figure 13: Schematic visualization of sampling in laminar air flow, Adapted from (Trotec GmbH, 2017)

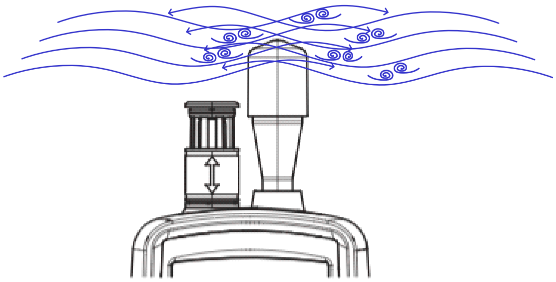

Figure 14: Schematic visualization of sampling in turbulent air flow, Adapted from (Trotec GmbH, 2017)

The tests should be taken several times to minimize coincidence errors and increase the reliability of the test results. After comparison and evaluating occurring alignments or deviations of the measured data, valid information about the influences of turbulent air flow while sampling is obtained.

4 CONCLUSION

The measuring of our air constituents allows us to keep track of the Earth's climate drivers and maintain an appropriate balance of aerosols in our atmosphere. Whereas the cooling effect of most air particles helps us to mask the greenhouse gas induced climate heating, overly immense concentrations of certain air particles entail the risk of harming our health and environment.

Current situations of global pandemics show us how much impact certain respirable particles, like viruses, can have on our well-being and how beneficial a precise estimation of their local and global distribution can be. Given the acknowledged impact aerosols have on our health, environment and Earth's climate, it requires us to gather reliable data to form the basis of air pollution policies and conserve a balance that comforts each and every stakeholder.

Locations of high particle emissions that often exhibit potential toxicity due to extraordinary particle concentrations of a certain kind, become hazardous and inaccessible for humans. Being able to measure those, allows us to receive information about some of the most relevant particle sources on the planet and enables us to take actions if necessary. Without the help of mobile measurement techniques some particle effects cannot be analysed properly because ground-based stations are not providing sophisticated results.

Diverse processes responsible for our climate are present at certain heights, hence alternative techniques are required. Many airborne measurement systems can reach those areas, such as blimps, fixed or flapping wing UAVs, but rotary wing drones have the additional advantage of not only being controllable in all three dimensions but also within high precision to obtain exact data where it is needed. Moreover, they provide the opportunity to measure data at difficult approachable locations and can hover at one specific spot for periods of time to allow for time-dependent measurements. Thus, researching ways to implement drones to the measurement process of aerosols serves the opportunity to enhance measurement possibilities and versatility.

The tests explained in this thesis will investigate the influences of the interaction of drones with the measurement process and reveal data that benefits the development of airborne measurement systems. Since they cannot cover all potential erroneous sources, they still need to evolve whilst the practical testing takes place to guarantee the best possible and reliable results.

Especially, in the last decade the development of airborne measurement systems has progressed steadily. They already showcase a significant value adding option to evaluate the global air particle distribution in former difficult accessible areas and allow us to act upon them. The future will further improve usability as it is already an essential advantage when operating drones. Together, the versatile and quick data gathering possibilities with the favourable financial aspect, will make the implementation of drones to the particle measurement process immensely beneficial for science.

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