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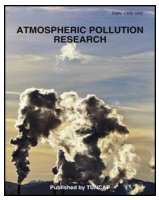

Ultrafine particles in inhabited areas in the Arctic - From very low to high concentrations

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ABSTRACT

The Arctic is considered a pristine environment, where pollution mainly originates from global sources. The present study examines particle number concentrations (PNCs) and the main sources of airborne ultrafine particles (UFPs, $d < 100$ nm) in the town Sisimiut and two nearby settlements, Sarfannguit and Itilleq, in West Greenland. Measurements were carried out during three weeks in April and May 2016. Air temperatures during the measurements ranged from −4.4 to +8.7 °C. A portable condensation particle counter (P-Trak) was used for the measurements. Results showed that the lowest concentrations were found during days with high wind speeds, with the lowest PNC average of 72 ± 11 cm^{-3} ($n = 9$) (12 m/s). Background concentrations were usually low compared to more densely populated countries, with a couple of exceptions, where there was no clear cause for elevated PNCs in a background area East of Sisimiut. Measured PNCs in the flue gas in the waste incineration plant in Sisimiut showed up to 334,976 cm^{-3} and are expected to be higher in the gas after it is released through the chimney. Average PNCs up to 77,009 ± 43,880 cm^{-3} ($n = 26$) were measured by a road located by the harbor in Sisimiut, while subsequent measurements at the same location showed much lower PNCs. The presence of heavy machinery elevated PNCs highly during two measurement events, giving PNCs up to 270,993 cm^{-3} but dropping to 1180 cm^{-3} 10 min later, after the vehicle had passed by. A measurement event in Sisimiut Airport while an aircraft landed and departed showed an average PNC of 44,741 ± 85,094 cm^{-3} ($n = 21$). Two 24-h measurements resulted in average PNCs of 2960 ± 5704 cm^{-3} and 3935 ± 10,016 cm^{-3} respectively.

1. Introduction

1.1. Ultrafine particles

Ambient ultrafine particles (UFPs) are airborne particles with a diameter less than 0.1 μm. Due to their small size, their mass is insignificant and the usual method of measuring UFPs is in particle number concentrations (PNCs) (number of particles pr. cm^3). UFPs can be primary particles that mainly originate directly from combustion processes, and one of the important sources is diesel driven road vehicles. However, UFPs may also be secondary particles formed from gases in the atmosphere. UFPs generally do not travel long distances since they tend to evaporate or aggregate to larger sized particles in the atmosphere (Hinds, 2000). Therefore, UFPs mainly pollute on local levels. Aggregated particles that are the size of fine particles ($PM_{2.5}$, $d < 2.5$ μm) can however be transported further (> 1000 km) and become a global pollutant (Hinds, 2000; Seinfeld and Pandis, 2006).

UFPs can contain black carbon (BC), which has a warming effect in the atmosphere. BC can settle on ice or snow covered surfaces, and affect the surface albedo by making the surface darker so that it absorbs sunlight more easily. This leads to faster melting of the ice and snow, which again contributes to rising sea levels. Furthermore, particles that contain BC are considered more health damaging than inorganic particles (Janssen et al., 2011). The large surface area of UFPs increases the

Abbreviations: UFP, ultrafine particles; PNC, particle number concentration; $PM_{2.5}$, fine particles; BC, black carbon; ATV, all-terrain vehicle; MIP, modified Danish straw incineration plants; AGL, above ground level; RH, relative humidity; WIP, waste incineration plant

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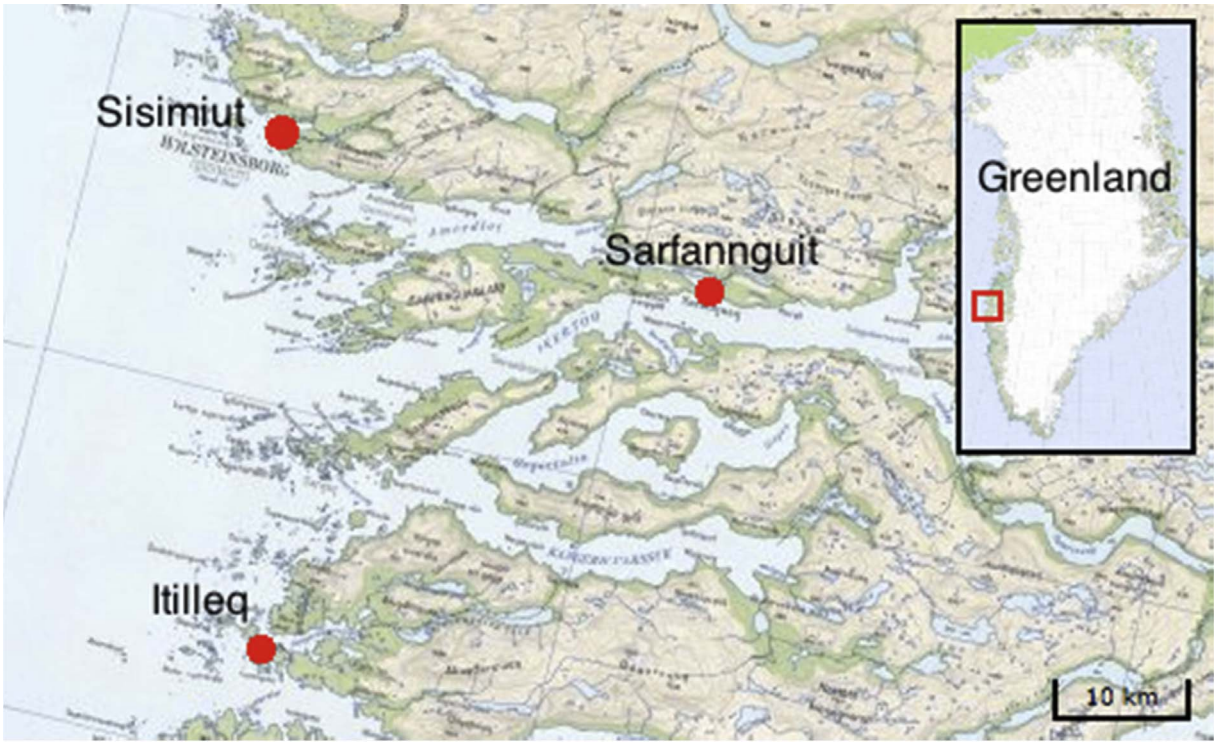

Fig. 1. The location of Sisimiut and the settlements Sarfannguit and Itilleq. Modified from Asiaq (2014).

risk of toxic substances adsorbing to the surface, which can be harmful when the particles are inhaled, as they can either deposit in the lungs or translocate further to the veins and other organs due to their small size. Some studies have suggested a relationship between UFP exposure and acute cardiovascular morbidity (Weichenthal, 2012). It has proven difficult to examine the exact relation between UFP exposure and adverse health effects in terms of an exposure-dose-response research. This is partly due to the fact that UFPs are local pollutants and can vary greatly in concentration even within a small area. Furthermore, people typically spend about 90% of their time indoor, and the UFPs seem not to transport easily from outdoor to indoor environment. Indoor activities, such as candle lights and other indoor pollution sources, will thereby cause a very different exposure to ultrafine particles. Larger particle fractions, such as $PM_{2.5}$, are on the other hand more uniformly distributed even in a big area, which makes studies on the related health effects easier, and they seem to translocate from outdoor to indoor environment more easily than UFPs. Therefore, larger particle fractions have already been assigned limit values for ambient air, while UFPs have not been assigned any limit values yet. An exception is the newest European exhaust emission standards (Euro 5 and Euro 6) that include a maximum PNC emitted in the exhaust pr. km travelled by new vehicles (European Commission, 2008, 2011).

UFPs, BC and sulfate concentrations have been measured at the Villum Research Station, Station Nord in northeast Greenland (Eckhardt et al., 2015; Massling et al., 2015; Nguyen et al., 2016). These measurements have provided information about background concentrations measured over long time periods in a remote Arctic area, where there are no obvious sources of UFPs. The PNCs measured at Villum Research Station can be very different from the concentrations in Greenlandic towns, as the nearest town is located approx. 1250 km from Villum Research Station, and the PNCs are highest close to the emission sources. UFPs observed at a remote location like this is, however, most likely the result of new particle formation from gaseous pollutants that have been long-range transported from the surrounding continents. Local air pollution is usually not considered as a concern in the remote towns of Greenland or the Arctic, where the population is scarce and manufacturing industries are negligible. Nevertheless, due to the remoteness of the towns, the technology used is often outdated and may therefore be a greater emission source than it could be with newer technology, as well as proportionally being a big contributor to air pollution in the small-sized towns. One of the few measurements of local air pollution that have been made in Arctic areas includes the effects of an 8-month landfill fire in Iqaluit in Arctic Canada (Weichenthal et al., 2015). During the fire, the air quality was measured at four stations 1.2–3.8 km from the fire. Their measurements revealed high $PM_{2.5}$ concentrations when the wind conditions were towards the measuring stations, although with average $PM_{2.5}$ concentrations below the 24-h Canadian ambient air quality standards. The present study examines the levels of UFPs in the Greenlandic town Sisimiut and two nearby settlements, Sarfannguit and Itilleq. Prior to this study, no measurements of UFPs had been made in an inhabited area in Greenland. Fine and coarse particles have earlier been measured to a small extent in this area, mainly as a part of student projects and related to the establishment of waste incineration plants (unpublished results). There is generally little to no control of any air pollutants in emissions and exhaust gasses in Greenland due to the lack of limit values that apply in the country.

1.2. Sisimiut

Sisimiut is the second largest town in Greenland, with approximately 5500 inhabitants, corresponding to 10% of Greenland's total number of inhabitants (Statistics Greenland, 2016a). The town is located on the west coast of Greenland (66°56′N, 53°40′W), approx. 40 km N of the Arctic Circle. The nearest inhabited areas are the settlements Sarfannguit (113 inhabitants) and Itilleq (85 inhabitants), located resp. 35 km ESE and 40 km S of Sisimiut (Fig. 1). For transportation between Sisimiut, the settlements and nearby lodges and during hunting, snowmobiles and dogsleds are used while there is snow cover, whereas all-terrain vehicles (ATVs) are used all year round. There are no road connections to Sisimiut, as with all inhabited areas in Greenland, so the way to arrive in the town is by airplane or boat. A domestic

airport is located approx. 2.5 km NW of the town's center. During winters, the fjords and the harbor are partly covered with ice, so mainly cargo and large passenger ships can operate to and from the town. In the summers, the harbor activities also include cruise ships, smaller passenger boats, trolleys and fishing boats.

As for all of Greenland, air polluting industry and production is minimal in Sisimiut, which reflects in the fact that the manufacturing industry comprises of only 1% of all employments in Sisimiut district in average pr. month (in 2014) (Statistics Greenland, 2015).

The waste management in Sisimiut consists of an incineration plant, established in year 2001 (Sigvardsen, 2011), and a landfill site. For the past 2–4 years, inhabitants have been able to sort biodegradable waste, glass, metal and hazardous waste, as well as hand usable items for direct reuse. Biodegradable waste is used in a pilot project for composting, while other sorted waste is reused, landfilled or exported to Denmark (Eisted and Christensen, 2011). The incineration plant is simple, and the air pollution control for the flue gas is solely electrostatic precipitators. The fly ash is handled as hazardous waste and shipped to Denmark and afterwards to Norway for final treatment, whereas the bottom ash is disposed of at the unlined disposal site. The energy produced by the incineration is recovered and partly used for district heating (Eisted and Christensen, 2011), but a large part of the energy and heat consumed in the town comes from a hydropower plant, implemented in 2010, and from private oil heaters in the homes.

Five other towns in Greenland have incineration plants comparable to the one in Sisimiut, while many smaller towns and settlements, including Sarfannguit and Itilleq, have small scale incinerators known as modified Danish straw incineration plants (MIPs) with no energy utilization and no flue gas treatment (Eisted and Christensen, 2011). The remaining towns and settlements have open landfills/disposal sites and/or uncontrolled combustion.

In Sarfannguit and Itilleq there are no asphalt roads, only gravel roads and pathways. Therefore, passenger cars are not used in the settlements, but ATVs and some heavy vehicles are used mainly for construction projects, snowplowing, waste collection etc. Most of the houses are supplied with oil-heaters and receive electricity from common diesel generator plants in the town.

2. Materials and methods

PNCs in the ambient air were measured in Sisimiut in the time period April 21 to May 12, 2016. Measurements in the settlements Sarfannguit and Itilleq were carried out on May 2, 2016. A P-Trak Ultrafine Particle Counter, model 8525 from TSI, was used for the measurements. The P-Trak used was brand new, factory calibrated and unused prior to these measurements. It measures the PNC every second, where after the average PNC pr. minute is used for further data processing. The P-Trak detects particles in the diameter size interval 0.02–1 μm and can count up to 500,000 particles cm^{-3} (TSI, 2012).

The duration of each measurement ranged from 2 to 90 min, with the exception of two 24-h continuous measurements. Measurement locations were chosen with the aim to measure the PNC in areas of suspected UFP pollution in Sisimiut as well as in Sarfannguit and Itilleq. The locations within Sisimiut are marked in Fig. 2. The main sources examined in this study were the waste incineration plant, road traffic, the airport and the construction sites. Other sources that were examined to less extent and will not be described in detail here, were the electricity plant with diesel generators in Sisimiut, which today is only used for emergency condition or during overload on the hydropower plant, and an area of single-family houses that are heated with private oil heaters. Background measurements were obtained in the outskirts of Sisimiut, where no suspected active sources of UFPs were nearby. Furthermore, the PNCs were measured over 24-h outside the Apisseq dormitory, in order to determine diurnal variation in the PNC. Some of the above-mentioned measurements were stationary, while others were carried out while walking slowly around with the P-Trak in the surrounding area, keeping the P-Trak carefully in a horizontal position as it cannot function otherwise, indicated by a beeping sound. The sampling height was in most cases between 70 and 130 cm above ground level (AGL), as the P-Trak had to be carried or observed by a person during the measurements, with the exception of the 24-h measurements that were taken from the 2nd floor, approx. 7 m AGL. During walking there is a theoretical influence on the measurements by the person handling the P-Trak. Unpublished measurements conducted at Department of Environmental Engineering, Technical University of Denmark show that up to 1/3 of UFPs are retained in persons during respiration. However, we estimate that this volume is negligible compared to the exchange rate of air during measurements.

Particle concentrations vary with meteorological conditions: temperature, humidity, wind speed and wind direction. Therefore, these parameters were measured with a Speedtech WindMate 300 handheld instrument each day of PNC measurements, and the interpretation supported by weather data from Asiaq - Greenland Survey's weather station in Sisimiut. The wind conditions in the PNC measurement period were compared to wind conditions during the time period January 1, 2004 to December 31, 2015 in order to evaluate whether the measurements were taken during typical meteorological conditions.

2.1. Waste incineration

The waste incineration plant in Sisimiut and the landfill site are located in the outskirts S of the town (no. 1 in Fig. 2). In 2006, approx. 2724 tons of waste were incinerated in the plant, corresponding to 505 kg pr. inhabitant pr. year (Eisted and Christensen, 2011). The electrostatic precipitators applied to treat the flue gas from the incineration are mainly aimed for removing bigger particles (fine, coarse), but not UFPs. The flue gas is subsequently released to the ambient atmosphere through a chimney (approx. 30 m high), but some of the UFPs are likely formed from gaseous pollutants in nucleation processes in the plume after the release from the chimney. It was possible to conduct a short campaign of PNC measurements on the flue gas seeping through a small opening in the pipes leading to the chimney. The PNC was also measured in the control and monitoring area of the incineration, which is separated by a glass window from the loading area of waste into the incineration chamber. This is an example of the working environment in the incineration plant. In order to see how the UFPs in the emitted flue gas influences the area around the plant, the PNC was measured close to apartment buildings on the roads Isikkviup Aqq. and Kussangasoq, approx. 200 m NE of the incineration plant. The houses are located on the top of a hill, around the same height as the chimney top of the incineration plant. Furthermore, the PNCs were measured in a nature area approx. 200 m S of the plant. This area includes a short hiking trail, where the highest point is approx. at the same altitude as the chimney top.

2.2. Road traffic

At the beginning of 2016, a total of 1352 motor vehicles were registered in Sisimiut, including 774 road vehicles, 57 construction machineries, 474 snowmobiles and 47 ATVs (Statistics Greenland, 2016b). Approx. 50% of the vehicles are diesel driven, while the other 50% runs on petrol. The newer snowmobiles have a four-stroke engine and run on petrol, while older snowmobiles have a two-stroke engine, which uses a mixture of petrol and oil and emits high amounts of pollutants including particulate matter, HC, CO and NO_X. Snowmobiles are used within the town, in the backcountry and for transportation to nearby settlements for the around 6 months of the year with snow cover. During the PNC measurement campaign, the temperatures were often above freezing point, and surface snow and ice was melting, leading to minimal snowmobile traffic. The asphalt road system in Sisimiut stretches over approx. 35 km. The driving pattern within the town is characterized by short trips, slow speeds and many starts and stops.

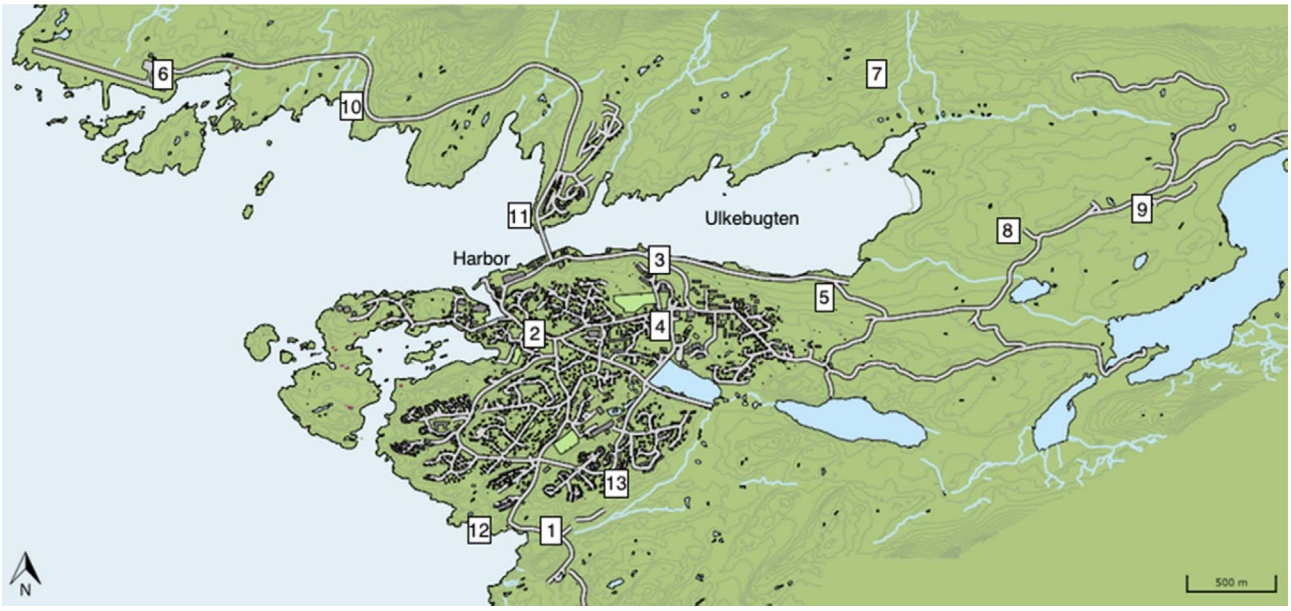

Fig. 2. The locations of PNC measurements in Sisimiut: (1) Waste incineration plant, (2) road traffic by the harbor, (3) road traffic by Ulkebugten, (4) construction site in central Sisimiut, (5) construction site by Ulkebugten, (6) Sisimiut Airport, (7)–(12) background measurements, (13) Apisseq, 24-h measurements. Modified from Asiaq (2014).

This is not an optimal driving pattern with respect to particle emissions, especially for diesel vehicles. Furthermore, vehicles are often kept idling outside stores and domestic houses, typically when the temperatures are cold. Vehicles in Greenland are most frequently imported from Denmark, which implies that they should comply with the European exhaust emission standards, limiting the PNC in the exhaust emissions of new vehicles. It is not given that all newly imported vehicles in fact do comply with these standards and that particulate filters and catalysts are properly maintained, since there is a lack of systematic control and inspection of vehicles in Greenland. In any case, there are no limit values for UFPs in the emissions of older vehicles.

The PNCs by two roads in Sisimiut, the corner of Nikkorsuit and Umiarsualivimmu close to the harbor (no. 2 in Fig. 2) and Muunup Aqq. by Ulkebugten (no. 3 in Fig. 2), were measured at different times during the campaign period. Nikkorsuit/Umiarsualivimmu is one of the most heavily trafficked areas in the town, while Muunup Aqq. is less trafficked. All measurements were on weekdays, where the traffic is usually heavier than in weekends. The number of vehicles driving past the P-Trak during the PNC measurements was counted on site by observing the traffic.

2.3. Construction sites

Construction is one of the biggest industries in Sisimiut, comprising approx. 11% of all employments in average pr. month in 2014 (Statistics Greenland, 2015). The town is expanding, with new family houses and apartment complexes rising in the district Akia, N of Ulkebugten fjord, and a few construction projects closer to the center of the town, such as by the Telepost center and one of the main grocery stores (no. 4 on Fig. 2). This site is also close to family houses, a kindergarten and a school. The PNCs were measured at this site and at a smaller construction site by Ulkebugten (no. 5 in Fig. 2). Heavy vehicles are also found outside of construction sites, as wheel loaders are used for snowplowing and for clearing flooded roads for melt- and rainwater, and septic tank trucks and other heavy vehicles are often driving around in the town. The influence of these vehicles on the PNC, in areas that are not construction sites, were observed during a 24-h measurement campaign outside the Apisseq dormitory and during a campaign in Itilleq.

2.4. Sisimiut Airport

Sisimiut Airport is located approx. 2.5 km NW of the town's center (no. 6 in Fig. 2). The airport can service short takeoff and landing (STOL) aircraft. There are in average 2.6 flight arrivals and departures pr. day, all domestic flights. The PNC was measured in the airport when a Dash-8 aircraft was landing, during handling, loading and takeoff, stretching over approx. 25 min in total.

2.5. The settlements

The settlements Sarfannguit and Itilleq (cf. Fig. 1) were accessed by boat and the PNCs measured for approx. 1 h in each settlement. In Itilleq, the weather conditions are usually similar to Sisimiut, as both are located at the mouth of fjords, next to the open sea. Sarfannguit is located in the bottom of a fjord, so the winds are often calmer and the summer temperatures higher than in Sisimiut. There are not as many possible sources of UFPs in the settlements as in Sisimiut, as motor traffic is minimal due to the absence of cars. The main possible sources are the MIP waste incineration plants, very few heavy vehicles, boats, ATVs and snowmobiles in the winters. Furthermore, there is a small fish factory in each settlement, an electricity plant with diesel generators and private oil heaters in the homes, which may contribute to elevated PNCs.

The incineration plants are located in the western part of each of the settlement. Usually, waste is only incinerated when wind conditions are favorable, which is when the wind direction is not from W, so the smoke will not affect the inhabited part of the settlements.

2.6. Background measurements

PNC measurements were carried out at a few locations in and around Sisimiut in order to examine the background concentration in this area, and to investigate how low they can be when no obvious sources of UFPs are nearby. The PNC measurements were performed while hiking around Ulkebugten fjord (no. 7 and 8 in Fig. 2), an area where no roads, houses or obvious sources of UFPs are nearby, as well as along a gravel road leading to the backcountry, E of the town (no. 9 in Fig. 2). Furthermore, the PNC was measured by a small beach close to the airport (no. 10 in Fig. 2), on the bridge leading to Akia and the

airport (no. 11 in Fig. 2), by the ocean close to the incineration plant (no. 12 in Fig. 2) and by the Apisseq dormitory (no. 13 in Fig. 2). Background PNCs were also often measured in the town before or after measurements by specific sources, during 24-h stationary measurements and in Itilleq.

2.7. 24-h measurements

The diurnal variation in PNC was measured by fitting a telescoping probe on the P-Trak, and placing the probe through an open window on 2nd floor of the Apisseq dormitory in the southern part of Sisimiut (no. 13 in Fig. 2), where it measured constantly for 24-h. Two 24-h measurements campaigns were carried out, one from Saturday to Sunday in the beginning of the campaign period and the other from Monday to Tuesday towards the end of the campaign. Apisseq is located in a residential area, approx. 70 m S/SE of a lightly trafficked road, and approx. 450 m NE of the waste incineration plant. The chimney of the plant is visible from the window where the measurements took place and is at a slightly lower elevation than the window. The main possible sources during the measurements included the road traffic, idling cars outside neighboring houses, snowplows, the flue gas from the incineration plant, cigarette smoke from neighbors and indoor sources such as cooking in the dormitory. The use of the telescoping probe typically results in a lower PNC compared to measuring without the probe. The effect was quantified six times on three different days in the campaign period, by conducting short (5–8 min) measurements with and without the probe right after each other. The measurements were stationary and conducted indoors in room temperature, with minimal possible effects that could enhance the variation of PNC with time. The effect resulted in average in a 20.5% higher PNC when the probe was not used, compared to the measurements with the probe. Therefore, the factor 1.205 was multiplied with the measured PNCs with the probe. The P-Trak was unaffected by the weather and low temperatures outside, since only the probe was placed through the window while the device itself was placed indoors in room temperature. Approx. every 8 h the alcohol wick in the P-Trak had to be recharged with the isopropyl alcohol that it uses to grow the particles into easier detectable and countable particles (TSI, 2012). The device was therefore turned off during each recharge for approx. 10–15 min. These were the only breaks in the otherwise continuous 24-h measurements.

3. Results

The meteorological conditions in Sisimiut during the PNC campaign period, supplied from Asiaq - Greenland Survey, consisted of hourly means for temperature, relative humidity (RH), precipitation, barometric pressure, wind speed and wind direction (Asiaq, pers. communication, 2016). Fig. 3 illustrates the variation in temperatures, RH and the precipitation pr. day in the campaign period. The mean temperature was $+1.3 \pm 3.0$ °C and mean RH 85 ± 13%. Total precipitation in the period was 100.3 mm. Barometric pressure was in average 1016.4 ± 6.0 hPa.

Air temperatures below zero can make outdoors measurements difficult, since they can decrease the battery life of the P-Trak, and the display starts fading. The P-Trak operation temperature is set to be between 0 and 38 °C in the manual (TSI, 2012), but PNC measurements conducted at temperatures slightly below zero appeared to be unaffected by the low temperature. Ten years of experience at Department of Environmental Engineering, Technical University of Denmark shows that the P-Trak operates unaffected down to approximately −5 °C, and then the LCD display begins to fade, while the particle counting appears to be unaffected at −5 °C. High humidity can affect the measurements, as the particles can increase to a size that is not detectable by the P-Trak. Furthermore, high humidity and precipitation can act as a scrubber and decrease the PNCs in the atmosphere (Jayamurugan et al., 2013).

The wind speed in the campaign period ranged from 0 to 12.5 m/s, with a mean of 3.2 ± 2.5 m/s. The wind rose in Fig. 4 illustrates the frequency of wind speeds and wind directions in the campaign period. These data were compared to long-term wind conditions in the period January 1, 2004 to December 31, 2015 in order to evaluate whether they showed expected behavior for this time of year. The 2004–2015 average wind speed in April was 3.2 m/s and 3.3 m/s in May. The 2004–2015 average maximum wind speed in April was 15.0 m/s and in May 13.5 m/s. This shows that the average wind speed in the PNC campaign period was normal for this time of year, while the maximum wind speed was slightly lower than it usually is in this season. The dominant wind direction in 2004–2015 was E (22%), followed by WNW (11%), where in the campaign period WNW was most frequent (17%), followed by E (14%). Apart from that, the wind directions were fairly normal in the campaign period, and the correlation between the two periods is significant, with a correlation coefficient of $r = 0.803$.

Results from the PNC measurements will in the following mainly be presented as PNC average ± standard deviation (particles cm^{-3}) for n minutes of measurement. Additionally, a maximum and/or minimum PNC is presented when relevant. The main results of the PNC campaign are summarized in Table 1. The PNCs are measured pr. second but an average PNC pr. minute is used unless otherwise stated.

3.1. Waste incineration

Inside the waste incineration plant, a short measurement was made on the flue gas seeping through an opening in the pipes leading the treated flue gas to the chimney of the waste incineration plant, resulting in a maximum PNC of 334,976 cm^{-3}. The concentration is expected to be higher further inside the pipes as well as in the ambient air after the flue gas is emitted through the chimney, as condensates are formed after the smoke cools down. The employees of the plant are exposed to a high PNC, as a 12-min measurement in the control and monitoring area of the incineration plant resulted in an average of 44,090 ± 3767 cm^{-3}.

The PNCs were measured on two different days by apartment buildings approx. 200 m NE of the incineration plant, and at approx. the same altitude as the chimney top. The wind was from southerly directions on both days, so the area may have been affected by the plume from the incineration plant. Furthermore, on May 12, the maximum PNC of 4178 cm^{-3} occurred at the same time as a truck drove past the incineration plant, a possible source of the excess particles.

The measurement in a nature area approx. 200 m S of the incineration plant took place at the top of a hill at approx. the same altitude as the chimney top. The wind came from N/NW at the time of the measurement, and therefore possibly spreading particles from the chimney towards the measurement location, which can be the reason for the elevated PNCs at this location.

3.2. Road traffic

Estimations of fuel consumption in Sisimiut were acquired with the help of Statistics Greenland and the local fuel distribution company, Sisimiut Olie ApS. Approx. 92% of the imported fuel in Sisimiut is diesel fuel (22,650,161 L in 2015) (Statistics Greenland, pers. communication, 2016). Approx. 70% of the diesel fuel is used for heating of houses, 20% for vehicles and 10% for ships and boats (Sisimiut Olie ApS, pers. communication, 2016). 6% of imported fuel is petrol (1,490,281 L in 2015) where approx. 60% of that is used for vehicles and 40% for ships and boats. The remaining 2% of imported fuel is aviation fuel. This estimates that approx. 4.5 mio. L diesel fuel is combusted pr. year by the road traffic in Sisimiut.

The PNCs were measured by the heavily trafficked road intersection Nikkorsuit/Umiarsualivimmu by the harbor and the less trafficked road Muunup Aqq. by Ulkebugten fjord. The timing and number of vehicles passing the P-Trak during each measurement is noted in Table 1 for the

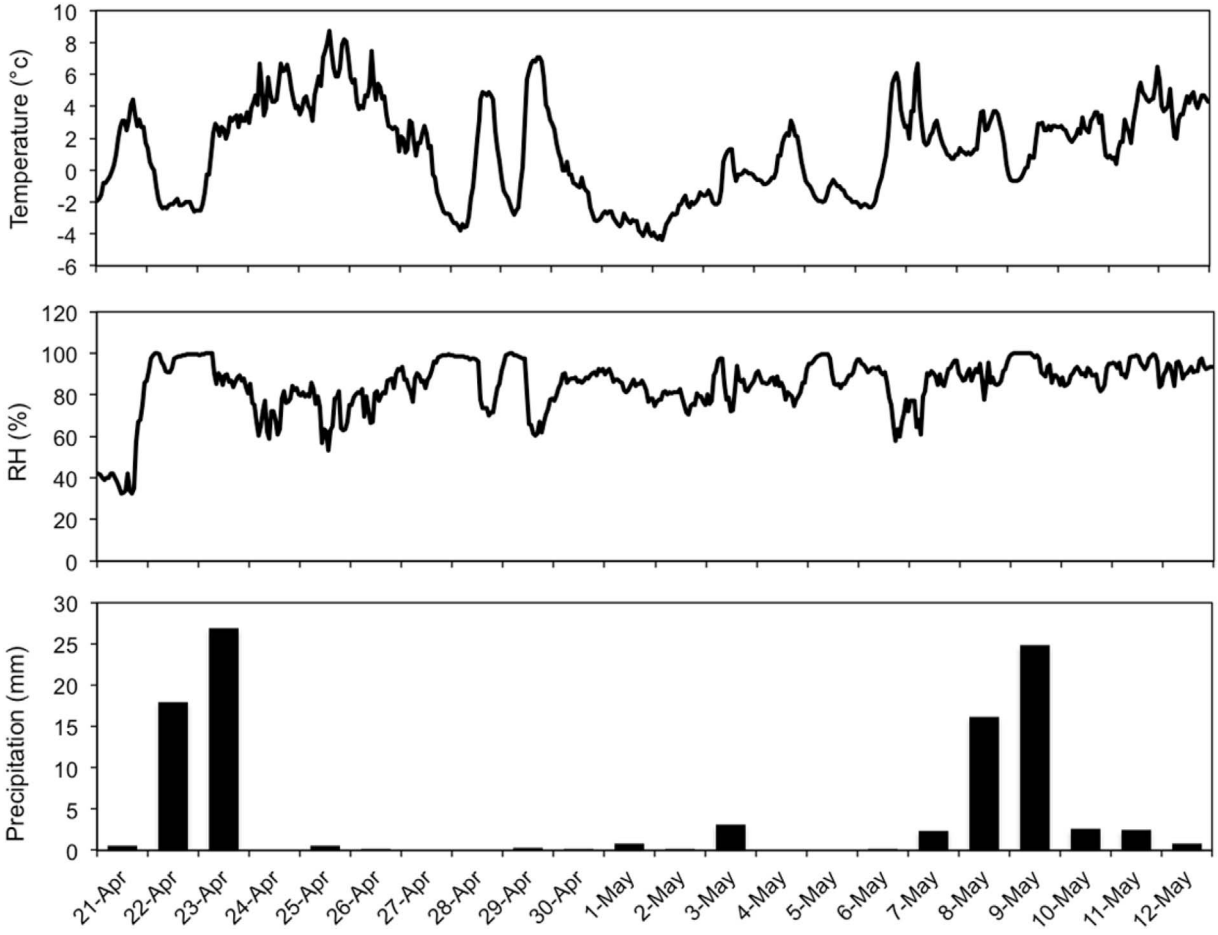

Fig. 3. Temperature (°C), relative humidity (RH, %) and precipitation pr. day (mm) in Sisimiut during the campaign period April 21 to May 12, 2016.

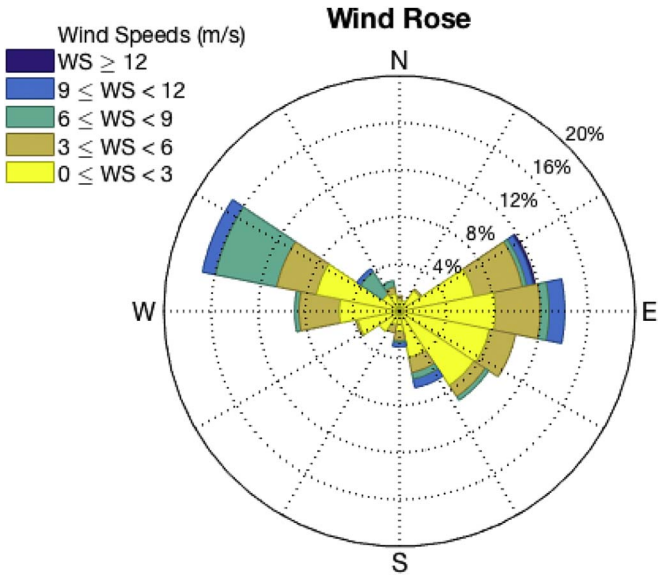

Fig. 4. Wind rose for Sisimiut during the campaign period April 21 to May 12, 2016.

comparison of heavy and light traffic. During the first measurement by Ulkebugten the vehicles were not counted, but the traffic was very light at that time, estimated to about 10 vehicles pr. hour.

The measurements by the harbor were taken while the traffic was rather heavy. The PNCs on April 25 were 12 times higher than the two subsequent measurements. A possible factor contributing to the elevated PNC is the wind direction, which was from SE/ESE on April 25, while during all the other measurement by the roads it was from westerly directions. Furthermore, RH was lower on April 25 than the subsequent measurement days, with 63% on April 25, 87% on April 27 and 96% on April 28. The max. PNC on April 25 occurred simultaneously with a tractor driving by the P-Trak. The PNCs were also measured outside Apisseq, a reference area with less traffic nearby, on April 25, shortly after the measurement by the harbor. This resulted in a 60 times lower PNC than by the harbor, implying that the measured PNCs by the harbor were greatly influenced by local sources.

3.3. Construction sites

The PNCs were measured at the centrally located construction site in Sisimiut (no. 4 in Fig. 2) on May 4 and May 6. The high maximum concentration on May 6 is assumed to be affected by heavy road traffic nearby. The PNC by a smaller construction site close to Ulkebugten fjord in Sisimiut (no. 5 in Fig. 2), also measured on May 4, was more stable than at the other site, probably due to fewer possible sources and less road traffic at this site, but also due to a shorter duration of the measurement. When measuring in Itilleq on May 2, a wheel loader drove from the harbor area towards the waste incineration in the western end of the settlement, increasing the PNC in the center of the settlement from 263 cm^{-3} to 39,864 cm^{-3}, with a few seconds up to 213,000 cm^{-3}. Furthermore, during a 24-h measurement by Apisseq, a snowplow drove by beneath the window where the P-Trak was located. This showed an increase from the average of 3935 cm^{-3} up to 270,993 cm^{-3}.

Table 1
Results from the PNC campaign, showing location and position in Fig. 2, date and time (GMT-2) of each measurement, mean PNC, standard deviation (SD), minimum and maximum PNC (1-min. average), number of measurements in minutes (*n*), and eventual other remarks (e.g. vehicle count pr. hour).

Location (position on map, Fig. 2)	Date	Time (hh:mm)	Mean (cm^{-3})	SD (cm^{-3})	Min (cm^{-3})	Max (cm^{-3})	*n* (min)	Other remarks
Waste incineration plant (WIP) (1)								
Inside WIP - Flue gas from pipes	April 29	13:31–13:34	125,005	25,954	102,524	153,408	3	Max value pr. second 334,976
Inside WIP - Control area		13:08–13:20	44,090	3767	37,063	49,855	12	
Nature area 200 m S of WIP	April 29	11:11–12:00	3234	652	2096	4846	49	
Apartment area	April 22	11:06–11:19	478	332	271	1340	13	
200 m NE of WIP	May 12	10:41–10:57	1120	900	534	4178	16	
Road traffic								
Nikkorsuit/Umiarsualivimmu	April 25	11:39–12:05	77,009	43,880	20,780	157,281	26	424 vehicles/h
By the harbor (2)	April 27	11:22–11:34	6023	2928	2671	12,936	12	355 vehicles/h
	April 28	11:44–12:18	6573	5514	2334	26,478	34	425 vehicles/h
Muunup Aqq.	April 26	01:52–02:10	450	120	376	861	18	–
By Ulkebugten fjord (3)		08:11–08:47	24,328	17,107	6965	89,137	36	96 vehicles/h
		13:49–15:23	22,871	22,717	6804	187,761	94	58 vehicles/h
	May 10	13:27–13:45	11,586	5156	6156	24,927	18	108 vehicles/h
Outside Apisseq (13)	April 25	13:07–13:20	1292	626	493	2402	13	–
Construction sites								
Construction site, central Sisimiut (4)	May 4	10:19–10:32	7758	5701	1166	17,900	13	
	May 6	09:51–10:02	8561	11,439	309	33,974	11	
Construction site, Ulkebugten (5)	May 4	10:43–10:46	5470	1583	3696	6740	3	
Center of Itilleq	May 2	13:38–13:44	19,216	15,695	299	39,864	6	Max value pr. second 213,000
During 24-h measurement at Apisseq (13)	May 9	13:07–13:20	43,422	75,847	6457	270,993	13	
Airport								
Sisimiut Airport (6)	May 6	12:43–13:04	44,741	85,094	314	366,316	21	20 m behind aircraft
Sarfannguit								
By incineration of honey bags	May 2	09:53–09:59	94,014	43,805	43,875	153,303	6	
In town		10:01–10:34	1123	1704	163	8313	33	
Itilleq								
Background	May 2	12:45–13:03	276	39	257	387	18	
In town		13:04–13:16 13:37–13:54	4686	10,076	263	39,864	29	
Background measurements								
Bridge to Akia (11)	May 1	14:15–14:22	82	4	76	88	7	
N/NE of Ulkebugten (7)		14:36–17:26 (with breaks)	174	25	126	220	44	
E of Ulkebugten (8)		17:48–18:24 (with breaks)	195	18	183	267	19	
Backcountry (9)	May 4	11:15–11:25	2592	112	2426	2748	10	
	May 11	16:25–16:45	10,611	1381	8109	12,990	20	
Beach (10)	May 4	14:47–14:50	367	6	361	372	3	
By the sea (12)	April 29	13:43–13:51	961	71	854	1063	8	
Apisseq (13)	May 8	15:44–15:53	72	11	54	90	9	
24-h measurements								
Apisseq (13)	April 23–24 (Sat - Sun)	17:41–17:41	2960	5704	137 (at 03:34)	128,057 (at 17:48)	1419	
	May 9–10 (Mon - Tue)	10:38–09:23	3935	10,016	107 (at 17:23)	270,993 (at 13:18)	1334	

3.4. Sisimiut Airport

The PNC measurement in Sisimiut Airport took place approx. 20 m E of the rear of an aircraft that arrived just after the measurement started. The wind speed during the measurement was 1 m/s from W. The PNC just before the aircraft landed, was 362 ± 229 cm^{-3} (n = 3). The PNC average over the 21 min that passed after the Dash-8 aircraft arrived, and until it had departed again, was 44,741 ± 85,094 cm^{-3}. During this time the motors were turned off, the aircraft was unloaded, refueled and loaded again. Then the motors were turned back on, and 3 min later the aircraft had departed. While the aircraft motors were turned off, PNCs up to 56,195 cm^{-3} were measured, which implies that the handling and loading equipment with diesel engines also emit high numbers of particles. Right after the aircraft motors were turned back on, the PNC increased to 366,316 cm^{-3}.

3.5. The settlements

During the measurement in Sarfannguit, the wind direction was from SW. Waste was not incinerated at the time of measurement since the wind could blow the smoke towards the inhabited area, but honey bags from the bucket toilets were nevertheless being burned in an open barrel close to the incineration plant, in the western part of the settlement. A short measurement close to this incineration showed a PNC average of 94,014 ± 43,805 cm^{-3}. After that, the PNCs were measured while walking away from the incineration plant through the settlement, and ended by the harbor in the eastern end of the settlement. The PNC maximum of 8313 cm^{-3} was found approx. 100 m E of the incineration, and the minimum of 163 cm^{-3} was found close to the harbor, approx. 700 m ENE of the incineration. The most likely sources of UFPs in the settlement during the measurement were the incineration of honey bags, an ATV, which picked up the garbage and honey bags and the diesel generators at the electricity plant. Other possible sources

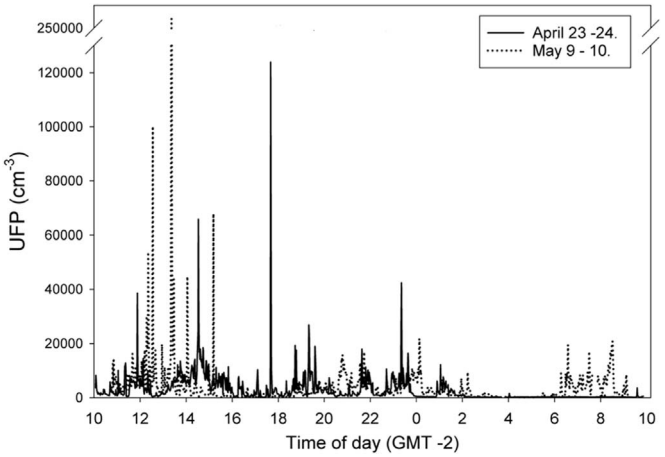

Fig. 5. The results from the two 24-h measurements outside of Apisseq.

include domestic heating by private oil heaters, boats by the harbor and indoor sources such as cooking.

In Itilleq, waste was incinerated in the incineration plant WNW of the settlement at the time of the PNC measurement. The smoke coming from the chimney was dark in the beginning, but turned brighter after measurement started. Weak W/SW winds blew the smoke towards a part of the inhabited area of the settlement. The background concentration in the settlement, measured N of the incineration plant where no effect from the incineration was found, was 276 ± 39 cm^{-3}. There were mostly the same possible sources of UFPs in the settlement as in Sarfannguit, except that instead of an ATV driving around in the settlement, a heavy wheel loader drove from the harbor area towards the incineration plant while measuring in the center of the settlement. The average PNC in the inhabited area between the incineration plant and the harbor, measured while walking through the settlement, was 4686 ± 10,076 cm^{-3}, where the minimum PNC of 263 cm^{-3} was found centrally in the settlement, approx. 330 m ESE of the incineration plant. The maximum PNC of 39,864 cm^{-3} was measured when the heavy wheel loader drove past the same location as where the minimum was found, as mentioned in section 3.3.

3.6. Background measurements

The main results from the background measurements in and around Sisimiut (no. 7–13 in Fig. 2) are noted in Table 1. The background concentration was measured while hiking slowly on the N and E sides of Ulkebugten fjord on May 1. The average speed of the hike was 2 km/h including many short breaks on the way, where some measurements were done while walking with the device, and others while standing still. The P-Trak was periodically turned on and off, in order to enable hiking on the uneven terrain where it was not possible to keep the P-Trak horizontal at all times, and also to prolong the battery time of the device as the low temperatures contribute to shortening of the battery time. The mean temperature was −3.5 °C and the mean wind speed was 8.5 m/s from NW. The furthest point of the hike was approx. 3 km NE of the center of Sisimiut. The PNC in this nature area, away from roads, houses and other possible sources of UFPs, was stable, with an average of 174 ± 25 cm^{-3}. Further E of Ulkebugten, along a gravel road but still away from houses and most UFP sources, the PNC was still low, 195 ± 18 cm^{-3}. The lowest PNC measured on this day was 76 cm^{-3}, which was found by the northern end of the bridge connecting the district Akia and the airport to the rest of Sisimiut, approx. 500 m N of the center of town. The high wind speed from NW can be the main reason for the low PNC, since sources in the town are unlikely to have an impact on this location due to the wind direction. May 8 was the stormiest days in the campaign period, with wind speeds up to 12 m/s mostly from SE, 3 °C and 40 mm precipitation over 24-h, and this resulted in the lowest PNC measured during the whole campaign, 54 cm^{-3}, or a 9-min average of 72 ± 11 cm^{-3}. This PNC was found outside 2nd floor of the Apisseq dormitory.

The PNCs were measured along the gravel road towards the backcountry, up to 3.5 km ENE of the center of Sisimiut, on May 4 and May 11. The first day, the weather was sunny, with a wind speed of 2 m/s from NW. The PNC was only measured at the furthest point from the town (no. 9 in Fig. 2), where the average PNC was 2592 ± 112 cm^{-3}. The second day, it was raining slightly and the wind was weak and from varying directions, approx. 1 m/s from SW/SE/E. The PNCs were measured while walking from the outskirts of town towards the furthest point of the route and back. The average for the whole route was 6974 ± 4390 cm^{-3} (n = 78). The average at the furthest point was 10,611 ± 1381 cm^{-3} or four times higher than measured on May 4 at the same location. The cause of the elevated PNCs is unknown.

When the PNC was measured at the beach close to Sisimiut Airport, approx. 1.5 km from the town's center, it was mostly sunny and the wind was approx. 2.2 m/s from WNW. No activity was in the airport at the time, so no obvious sources were affecting the area, which had a PNC average of 367 ± 6 cm^{-3}.

The PNC was also measured by the sea SSW of Sisimiut, close to the incineration plant. The wind came from WNW or directly from the ocean, so there should be minimal influence from sources of UFPs from the town. The PNC average was 961 ± 71 cm^{-3}.

Furthermore, the background PNCs within the town were often measured before or after other measurements, where the PNCs often were in the interval 400 to 500 cm^{-3}, when no evident sources were nearby.

3.7. 24-h measurements

The results of the two 24-h measurements taken on April 23–24 and May 9–10 outside the window of Apisseq are illustrated in Fig. 5. During April 23–24, the mean temperature was 4.5 ± 1.3 °C, RH 75 ± 10%, wind speeds 2.5 ± 0.9 m/s mostly from northeastern directions, and only 0.1 mm accumulated precipitation during the measurement. During May 9–10, the temperature was 2.3 ± 0.6 °C, RH 91 ± 4%, wind speeds 2.2 ± 1.6 m/s from varying directions and 5.9 mm accumulated precipitation. The overall PNC maximum of 270,993 cm^{-3} occurred on May 9 while a snowplow passed by right below the window where the measurement took place. Low PNCs were observed during the early morning between 2:30 and 6:00 on both 24-h, where on April 24 the average was 299 ± 117 cm^{-3}, and on May 10 it was 458 ± 404 cm^{-3}. Low PNCs were also observed during the afternoon on May 9, where the average was 493 ± 436 cm^{-3} (n = 209) with an overall minimum of 107 cm^{-3} at 17:23.

4. Discussion

4.1. Waste incineration

Since it was not possible to measure the PNC directly inside the pipes containing the flue gas or at the chimney top due to safety reasons, the PNCs emitted to the ambient air after the electrostatic precipitator are still unknown. They are assumed to be higher than the measured PNCs in the flue gas seeping through an opening in the pipes, as condensates are formed in the atmosphere when the smoke cools down, leading to a higher PNC. Buonanno and Morawska (2015) reported a median PNC of 5500 cm^{-3} at the stack of Italian and Danish waste incinerators, which is several factors lower than found in the present study. The emission of particles from waste incinerators is dependent on the efficiency of the flue gas treatment, where electrostatic precipitators should have a high efficiency for removing particles less than 5 μm (Buonanno and Morawska, 2015). However, bag filters provide even higher removal efficiencies and are used in the most modern incineration plants (Jones and Harrison, 2016). With the use of

bag filters, the number of UFPs measured in the close vicinity of incinerators is found similar level to background concentrations (Jones and Harrison, 2016). This is due to the dilution effects and the concentration is dependent on the flue gas treatment, flue gas velocity, chimney height and ambient wind speeds (Scungio et al., 2015). The PNCs in the nature area close to the Sisimiut incineration plant were elevated compared to the low background concentrations around the town, but comparable to background concentrations in European countries (Buonanno and Morawska, 2015; Ellermann et al., 2015). Qeqqata municipality is currently considering transporting waste from the nearby settlements, including Sarfannguit and Itilleq, to Sisimiut, instead of using the MIP incinerators in the settlements. This is considered in order to avoid high costs related to renovation of the MIP incinerators, including implementation of a flue gas treatment and increasing the capacity, and rather focus on adjusting the incineration plant in Sisimiut. The dioxin level in fly ash from a Greenlandic incineration plant with electrostatic precipitator was found to be 10 times higher than for Danish incineration plants with state of the art air pollution control systems (Dias-Ferreira et al., 2016), however the dioxin level in the flue gas was not measured. To quantify the PNCs and other contaminants in the flue gas emitted from the Greenlandic incineration plants, further measurements should be made. Then it could also be assessed how the flue gas treatment could be improved.

4.2. Road traffic

There were many possible sources of UFPs very close to the measurement location by the harbor, besides the road traffic. These include ships or boats, neighboring restaurants and shops, the fish factory and family houses. There were no such obvious sources right by the location by Ulkebugten, but in the near distance, uphill from the measurement location, apartment blocks, a hospital and an ongoing construction project were located.

For a comparison of UFPs by roads in more densely populated countries, a long-term measurement of the PNCs by the heavily trafficked road H. C. Andersens Boulevard in Copenhagen was carried out in 2014 (Ellermann et al., 2015). The particles measured here had a mobility diameter between 6 and 700 nm, or slightly smaller than the particles measured by the P-Trak in the present study. Furthermore, the PNCs in Copenhagen were measured continuously, resulting in an average that includes the diurnal variation in PNC, in contrast to the short-term measurements carried out in the present study. The average PNC found by H. C. Andersens Boulevard was approx. 14,000 cm^{-3}. Compared to this, some of the PNCs measured by the two roads in Sisimiut are therefore relatively high, especially considering the fact that the traffic in Sisimiut is negligible compared to Copenhagen. The reason for the large difference could be the lack of proper particulate filters and catalysts on the vehicles in Sisimiut.

4.3. Construction sites

It is evident that the presence of a heavy vehicle in an area with an otherwise low PNC leads to a high increase in the PNCs. The duration of the elevated PNC depends on how fast the vehicle passes the area. An example of this was when a heavy loader passed the P-Trak while measuring in Itilleq, where for a few seconds, the PNC increased up to 213,000 cm^{-3}, but since the vehicle passed by relatively fast, the 1-min average was only 39,864 cm^{-3}. Two minutes later, the PNC had dropped to 718 cm^{-3}, which still is almost three times higher than the background concentration in Itilleq.

4.4. Sisimiut Airport

Air pollution coming from Sisimiut Airport can have some influence on the town, especially when the wind direction is from NW, since the town is only in approx. 2.5 km distance in straight line, SE of the airport. As one of the most frequent wind direction is WNW, this is a reason for concern. The PNCs measured in the airport are though a better indication of the working environment in the airport, as the airport staff is exposed to the highly elevated PNCs close to their sources 2.6 times pr. day in average.

4.5. The settlements

The incineration of honey bags in Sarfannguit affected the area at least 100 m E of the incineration with elevated PNCs. 700 m further E, by the harbor and the eastern end of the settlement, the PNC was as low as 163 cm^{-3}, so there is no obvious effect of the incineration in this distance. In Itilleq, the PNCs by the houses closest to the incineration plant were elevated compared to the background PNC, but other sources, such as from within the houses, may have contributed as well. In the center of the settlement it was evident that the heavy wheel loader was the largest contributor to the temporary elevated PNCs.

4.6. Background measurements

It is evident that the PNCs in and around Sisimiut can be extremely low when mostly unaffected by human activity. The measurements while the wind speed was the highest resulted in the lowest PNCs averages measured during the study, 72 cm^{-3} and 82 cm^{-3}. The background PNCs in the town did usually not exceed 500 cm^{-3} when no evident sources of UFPs were nearby. A few measurements showed elevated PNCs in areas where they were expected to be lower, such as in the backcountry, ENE of the town, where no obvious sources were nearby. It is unknown what caused the elevated PNCs, and because of the rainy weather and high relative humidity in the area (> 90%) we would assume low PNCs, due to following: i) Rain normally cleans the air, ii) UFP will decrease in number due cluster formation in high humidity iii) apparent low ozone concentration and levels UV radiation (due to the weather), and the compounds normally stimulate particle formation.

PNCs and new particle formation in northeast Greenland have been examined by the group Nguyen et al. (2016). In 2012, the seasonal variation of PNCs was measured in Villum Research Station, Station Nord. The PNC average in April and May 2012 was 231 cm^{-3} and 221 cm^{-3} respectively. This describes the background concentration in a high Arctic area. The nearest possible source of UFPs was a Danish military base, located 2.5 km SE of the measurement site. This coincides well with many of the measurements of present study, where background concentrations were often in the same order of magnitude.

The background PNCs in Greenland are much lower than in more densely populated countries and non-Arctic sites. In Denmark, long-term measurements from 2014 have shown average PNCs of approx. 3000 cm^{-3} in a rural area, or around 10 times higher than the Greenlandic background, and approx. 4500 cm^{-3} in an urban background area (Ellermann et al., 2015).

4.7. 24-h measurements

The reasons for the peaks in the graph in Fig. 5 are not clear except for the highest peak that was caused by a snowplow passing by. Other possible sources are the road traffic and idling cars nearby, the flue gas from the incineration plant, cigarette smoke from neighbors and indoor sources such as cooking. The lowest PNCs during these measurements were as low as some of the background measurements had shown. The diurnal variation in the 24-h measurements indicates that there is much less activity of UFP sources in the town during the night and early morning than there is during the daytimes, reflecting human activity.

5. Conclusions

Periodically, the measured PNCs were very high considered the

remoteness of the location, the small population and limited number of possible sources of UFP emissions. The presence of vehicles without proper particulate filters, construction or other heavy machinery or aircrafts seem to contribute the most to elevated PNCs, but many of these cases are temporary and may only last for few minutes. Conflicting with the majority of the results, a measurement in the backcountry showed that the PNC could also be elevated even though no obvious sources were in the nearest distance. Most background measurements showed low PNCs, with the lowest PNCs occurring during days with high wind speeds.

The measurements performed in the present study provide a screening of the PNC situation in a remote, Arctic town and settlements, and can be used as a starting base or a reference line for future measurements in this or other Arctic areas. Future research should include measurements during other seasons of the year than in the present study, since the air temperatures and other meteorological conditions in this area can vary greatly between the seasons, and have different effects on the PNC as well as other air pollutants. Possible sources of UFPs that were not directly included in the present study can be examined, such as emissions from ships and boats in the area, indoor heating methods and snowmobiles. These can have contributed to the background concentration in the measurement locations in present study.

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References

Asiaq, 2014. NunaGis - CB kort. http://en.nunagis.gl/, Accessed date: 29 September 2016.

Buonanno, G., Morawska, L., 2015. Ultrafine particle emission of waste incinerators and comparison to the exposure of urban citizens. Waste Manag. 37, 75–81. http://dx.doi.org/10.1016/j.wasman.2014.03.008.

Dias-Ferreira, C., Kirkelund, G.M., Jensen, P.E., 2016. The influence of electrodialytic remediation on dioxin (PCDD/PCDF) levels in fly ash and air pollution control residues. Chemosphere 148, 380–387. http://dx.doi.org/10.1016/j.chemosphere.2016.01.061.

Eckhardt, S., Quennehen, B., Olivié, D.J.L., Berntsen, T.K., Cherian, R., Christensen, J.H., Collins, W., Crepinsek, S., Daskalakis, N., Flanner, M., Herber, A., Heyes, C., Hodnebrog, Huang L., Kanakidou, M., Klimont, Z., Langner, J., Law, K.S., Lund, M.T., Mahmood, R., Massling, A., Myriokefalitakis, S., Nielsen, I.E., Nøjgaard, J.K., Quaas, J., Quinn, P.K., Raut, J.-C., Rumbold, S.T., Schulz, M., Sharma, S., Skeie, R.B., Skov, H., Uttal, T., von Salzen, K., Stohl, A., 2015. Current model capabilities for simulating black carbon and sulfate concentrations in the Arctic atmosphere: a multi-model evaluation using a comprehensive measurement data set. Atmos. Chem. Phys. 15, 9413–9433. http://dx.doi.org/10.5194/acp-15-9413-2015.

Eisted, R., Christensen, T.H., 2011. Waste management in Greenland: current situation and challenges. Waste Manag. Res. 29 (10), 1064–1070. http://dx.doi.org/10.1177/0734242X10395421.

Ellermann, T., Nøjgaard, J.K., Nordstrøm, C., Brandt, J., Christensen, J., Ketzel, M., Massling, A., Jensen, S.S., 2015. The Danish Air Quality Monitoring Programme. Annual Summary for 2014. Aarhus University, DCE – Danish Centre for Environment and Energy, pp. 64 Scientific Report from DCE – Danish Centre for Environment and Energy No. 162.

European Commission, 2008. Commission regulation (EC) No 692/2008 of 18 July 2008. Off. J. Eur. Union 1–136.

European Commission, 2011. Commission regulation (EU) No 582/2011 of 25 May 2011. Off. J. Eur. Union 1–168.

Hinds, W.C., 2000. Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles, second ed. John Wiley & Sons.

Janssen, N.A.H., Hoek, G., Simic-Lawson, M., Fischer, P., van Bree, L., ten Brink, H., Keuken, M., Atkinson, R.W., Anderson, H.R., Brunekreef, B., Cassee, F.R., 2011. Black carbon as an additional indicator of the adverse health effects of airborne particles compared with PM10 and PM2.5. Environ. Health Perspect. 119 (12), 1691–1699. http://dx.doi.org/10.1289/ehp.1003369.

Jayamurugan, R., Kumaravel, B., Palanivelraja, S., Chockalingam, M.P., 2013. Influence of temperature, relative humidity and seasonal variability on ambient air quality in a coastal urban area. Int. J. Atmos. Sci. 2013, 1–7. http://dx.doi.org/10.1155/2013/264046.

Jones, A.M., Harrison, R.M., 2016. Emission of ultrafine particles from the incineration of municipal solid waste: a review. Atmos. Environ. 140, 519–528. http://dx.doi.org/10.1016/j.atmosenv.2016.06.005.

Massling, A., Nielsen, I.E., Kristensen, D., Christensen, J.H., Sørensen, L.L., Jensen, B., Nguyen, Q.T., Nøjgaard, J.K., Glasius, M., Skov, H., 2015. Atmospheric black carbon and sulfate concentrations in Northeast Greenland. Atmos. Chem. Phys. 15, 9681–9692. http://dx.doi.org/10.5194/acp-15-9681-2015.

Nguyen, Q.T., Glasius, M., Sørensen, L.L., Jensen, B., Skov, H., Birmili, W., Wiedensohler, A., Kristensson, A., Nøjgaard, J.K., Massling, A., 2016. Seasonal variation of atmospheric particle number concentrations, new particle formation and atmospheric oxidation capacity at the high Arctic site Villum Research Station, Station Nord. Atmos. Chem. Phys. 16, 11319–11336. http://dx.doi.org/10.5194/acp-16-11319-2016.

Scungio, M., Buonanno, G., Arpino, F., Ficco, G., 2015. Influential parameters on ultrafine particle concentration downwind at waste-to-energy plants. Waste Manag. 38, 157–163. http://dx.doi.org/10.1016/j.wasman.2015.01.008.

Seinfeld, J.H., Pandis, S.N., 2006. Atmospheric Chemistry and Physics: from Air Pollution to Climate Change, second ed. Wiley, New York.

Sigvardsen, S., 2011. Waste Incineration in Greenland - Strategy and Organization. Rambøll, Copenhagen, Denmark (in Danish).

Statistics Greenland, 2015. Main employment for permanent residents by time, industry, district and gender [AREBFB4]. http://bank.stat.gl/AREBFB4, Accessed date: 10 June 2016.

Statistics Greenland, 2016a. Population in localities January 1st 1977-2016 [BEEST4]. http://bank.stat.gl/BEEST4, Accessed date: 24 May 2016.

Statistics Greenland, 2016b. Registered motor vehicles by district [ENEMO2DI]. http://bank.stat.gl/ENEMO2DI, Accessed date: 17 November 2016.

TSI, 2012. P-TRAK Ultrafine Particle Counter Model 8525-Specifications. TSI Incorporated.

Weichenthal, S., 2012. Selected physiological effects of ultrafine particles in acute cardiovascular morbidity. Environ. Res. 115, 26–36. http://dx.doi.org/10.1016/j.envres.2012.03.001.

Weichenthal, S., Van Rijswijk, D., Kulka, R., You, H., Van Ryswyk, K., Willey, J., Dugandzic, R., Sutcliffe, R., Moulton, J., Baike, M., White, L., Charland, J.-P., Jessiman, B., 2015. The impact of a landfill fire on ambient air quality in the north: a case study in Iqaluit, Canada. Environ. Res. 142, 46–50. http://dx.doi.org/10.1016/j.envres.2015.06.018.