Effects of rocket launches in Ny-Ålesund, 2018 - 2019

Observations of snow and air samples

Wenche Aas[1], Jean-Charles Gallet[2], Anne Karine Halse[1], Ove Hermansen[1], Øyvind Mikkelsen[3], Christina A. Pedersen[2], Andrea Spolaor[4], Kjersti Tørnkvist[1], Hilde Uggerud[1]

[1] NILU – Norwegian Institute for Air Research, Kjeller, Norway
[2] The Norwegian Polar Institute, Tromsø Norway
[3] Norwegian University of Science and Technology, Trondheim, Norway
[4] ISP-CNR, Institute of Polar Science. National Research Council of Italy

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<tr><td colspan="2">AUTHOR(S)
Wenche Aas (NILU), Jean-Charles Gallet (The Norwegian Polar Institute), Anne Karine Halse (NILU), Ove Hermansen (NILU), Øyvind Mikkelsen (NTNU), Christina A. Pedersen (The Norwegian Polar Institute), Andrea Spolaor (ISP-CNR), Kjersti Tørnkvist (NILU), Hilde Uggerud (NILU)</td><td>QUALITY CONTROLLER

Kjetil Tørseth</td></tr>
<tr><td colspan="2">REPORT PREPARED FOR

Ny-Ålesund Science Managers Committee (NySMAC)
Norwegian Polar Institute, Sverdrup, 9173 Ny-Ålesund, NORWAY
Att.: Christina A. Pedersen</td><td>CONTRACT REF.

NySMAC, Christina A. Pedersen</td></tr>
<tr><td colspan="3">ABSTRACT

The report summarizes the results from additional snow sampling and regular monitoring activities in connection to the rocket launch in Ny-Ålesund 7 Dec 2018, 26 Nov 2019 and 10 Dec 2019 to document possible impacts on environment and on the monitoring activities in Ny-Ålesund. An enhanced deposition of aluminium (Al) and iron (Fe) on the local environment due to the rocket launch is observed.</td></tr>
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<tr><td colspan="3">ABSTRACT (in Norwegian)

Rapporten oppsummerer resultatene fra ekstra analyser av snøprøver samt pågående overvåkingsaktiviteter i forbindelse med rakettoppskytingen i Ny-Ålesund 7. desember 2018, 26. november 2019 og 10. desember 2019 for å dokumentere mulige påvirkninger av rakettoppskyting på miljøet og overvåkingsaktivitetene i Ny-Ålesund. Det observeres en økt avsetning av Al og Fe i Ny-Ålesund-området som skyldes utslipp fra rakettoppskytingen.</td></tr>
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Contents

Summary

Ny-Ålesund is an internationally acknowledged research station, facilitating and hosting research projects and long-term observation series. Everyone operating at or from the station is working to keep the environmental footprint of all activities as small as possible. The station constantly focuses on reducing all local sources of pollution , and has procedures for documenting relevant sources. .

In December 2018 and November-December 2019, Andøya Space launched different rockets in Ny-Ålesund. To evaluate how this may impact the local environment around Ny-Ålesund and potentially the research and monitoring in the area, a sampling campaign was conducted. Snow samples were taken at several locations and analyzed for trace elements and selected organic pollutants before and after the launches. In addition, snow samples from regular monitoring over two small local glaciers, and atmospheric observations of aerosols and gases at Zeppelin, were used to evaluate if these areas were impacted. Furthermore, booster debris observed in the impact areas were identified.

Snow samples from Ny-Ålesund showed elevated levels of aluminium (Al), probably due to the rocket launches, and there were increased concentrations of some chlorinated organic pollutants, but this is more difficult to assign to the launches. There were also some small impacts on the atmospheric observations of aerosol properties at Zeppelin and Gruvebadet, but not significant and over a very short time periods. Time series (2017-2020) from snow sampling from two small local glaciers was easier to use in order to assess and quantify of the impact of these rocket launches. Results from the snow samples show that the estimated total contribution of the launches, compared to the annual deposition, was estimated to be between 6-27% for iron (Fe) and 14-25% Al.

Debris from the booster rocket including scrap metal, insulation material, electric contacts were observed in Brøggerdalen, and there is indication that this may have caused contamination in the overbank sediments.

It is important that any activity in Ny-Ålesund has minimum environmental impact, both to preserve the pristine environment itself as well as keeping the site representative for study long-term changes in the Arctic environment. NySMAC agreed on the following recommendations (53rd NySMAC meeting, Nov. 2020):

- ***To us, Ny-Ålesund is not an ideal site for rocket launches****. The Ny-Ålesund research community works intensively to decrease negative environmental impact of Ny-Ålesund activities to keep it as a reference site to study long term changes in the Arctic environment. Activities like rocket launches have unfortunately undoubtedly a potential to jeopardize this effort.*
- *For planned, but not yet approved future activities involving rocket launches we propose:*
    - *comprehensive environmental assessment plan including complete analysis of rocket exhaust (certified by independent laboratory)*
    - *early discussion on special conditions and needs to avoid unnecessary risk on ongoing activities.*
- *To be able to conduct targeted analysis to assess possible contamination of sampling sites we need complete chemical composition of rocket fuel, if complete analysis of rocket exhaust is not available.*
- *We propose to resume the discussion under which conditions rocket launches can take place in Ny-Ålesund. All relevant parties in Ny-Ålesund should be given the opportunity to provide input to this discussion.*

- *A detailed description of the conditions under which rocket launches can take place should be integrated part of any future plans for additional rocket launches beyond those already approved.*
- *Monitoring possible impact of rocket launches on environment and research activities of other groups active at Ny-Ålesund requires significant allocation of resources and manpower. For future rocket campaigns these costs should be covered entirely by the operator or project owner.*

Effects of rocket launches in Ny-Ålesund, 2018 - 2019 Observations of snow and air samples

1 Introduction

In December 2018 and November-December 2019 Andøya Space Center launched four rockets in Ny-Ålesund, and to evaluate how this may impact the environment in Ny-Ålesund as well as the research and monitoring in the area, samples were taken before and after these launches. The fuel content of the different rockets is not known in details, but for the launch in 2018 the content was as follows:

- 16% Atomized aluminum powder (fuel)
- 69.8% Ammonium perchlorate (oxidizer)
- 1.2% Ironoxide powder (catalyst)
- 12% Polybutadiene acrylic acid acrylonite (binder)
- 2% Epoxy curing agent

In 2018 there was a rocket launch 7 Dec. with two rockets, one at 11:06 and one at 11:08 UTC. In 2019 there was one launch 26 Nov at 07:43 UTC and one at 10 Dec 09:30 UTC.

Snow sampling was conducted before and after the rocket launches, in order to detect possible deposition of contaminants (Table 1). In addition, regular monitoring of atmospheric composition and snow sampling on glaciers were evaluated to check potential impact on these two compartments (Table 1).

Table 1: Overview of sampling strategy in connection to the rocket launches in 2018 and 2019

	7 Dec 2018		26 Nov 2019 and 11 Dec 2019	
By whom	Samples	Analysis	Samples	Analysis
NILU	Snow samples (2x6 samples before and after launch)	Trace elements (Al, V, Cr, Fe, Co, Ni, Cu, Zn, Cd, Pb)	Snow samples (2x6 samples before in between and after launch)	Trace elements (Al, V, Cr, Fe, Co, Ni, Cu, Zn, Cd, Pb)
	Snow samples (pooled)	POPs (dioxins, furans, dioxin like PCBs)	Snow samples (pooled)	POPs (dioxins, furans, dioxin like PCBs)
NPI and CNR-ISP	Snow samples (screening)	Al, Fe, NH_4^+,NO_3^-	Snow samples (2x6 sampling sites before in between and after launch)	Trace elements (Na, Mg, Al, K, Ca, Ti, Fe, Cr, Mn, Ni, Cu, Zn, Sr, Cd, Ba, Pb, Li, V, Co, As, Rb, Mo, Ag, Sb, Cs, Tl, U)
			Snow samples	Black carbon (BC)
NTNU			Overbank sediments	Summer 2020 Trace elements and PAHs, PCBs, BTX, selected aliphatic/aromatic compounds
CNR-ISP	Regular monitoring from glacier snow sampling (inorganic ions and trace elements) Regular monitoring of atmospheric composition at Gruvebadet			
NPI	Regular BC monitoring at glacier snow sampling and Gruvebadet			
NILU/SU	Regular monitoring at Zeppelin (atmospheric chemical composition and aerosol properties)			

2 Sampling sites and protocol

2.1 Snow sampling

In 2018, snow sampling were done at 6 different locations (Figure 1, Table A.1), and two samples were collected at each location with 5m distance, with exception of Corbel where only one snow sample was taken. Samples were collected prior to launch at 3 different days (4-6 Dec; 7 Dec) and at launch day (12 Dec.) The goal was to do sampling of loose snow, but unfortunately the snow was rather hardpacked. Approximately 2 cm of fresh snow had deposited between first samples and launch, but nothing deposited between launch and second sampling (See Chapter 3.1 on Meteorology). All the collected samples were analyzed for trace elements (Table 1), while the samples were pooled to get enough material for POP analysis.

In addition, surface snow samples were collected during the first 24 hours after the launch as well as after 3, 7 and 15 days at the clean area close to Dirigibile Italia in Ny-Ålesund, at Gruvebadet for analysis of some trace elements and nitrogen species.

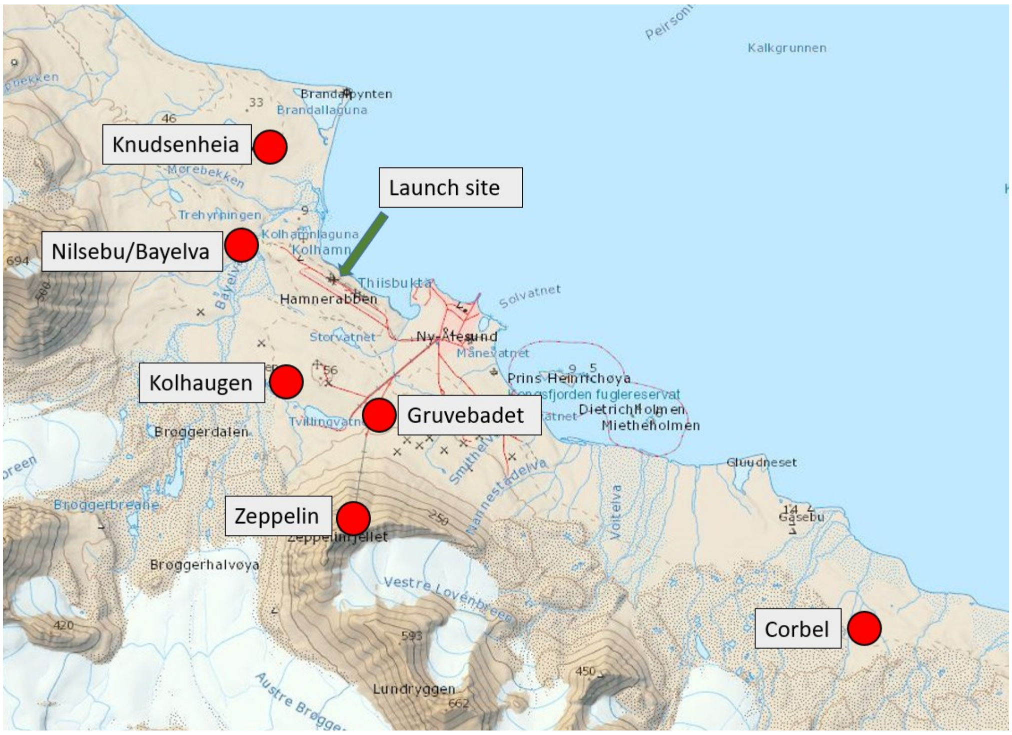

Figure 1: Sampling location for snow samples in 2018, coordinates in Table A.1.

In 2019, snow samples were collected at six sites around the airport prior to the rocket launches (Figure 2), some locations identical samplingsites in 2018 . For more details see Annex Table A.2. More comprehensive analysis was done at the three sites closest to the launch site (1, 2 and 3), as we anticipate these to be the most affected by the launch activity. We also included samples of two glacier (Midtre Lovenbreen (MLB) and Brøggerbreen (BRG)), where sampling was done during spring time. Snow samples from the years 2017-2020 (monitoring) were compared to evaluate potential impact of the launches.

In 2019 surface snow samples (the top first snow layer) and bulk samples (integrated entire snow column) were collected. The idea is to estimate possible contribution of launching a rocket on deposition of trace elements over snow, as most of the emitted particles will be dry deposited at the snow surface. Samples for analysis of black carbon (BC) were also collected at the exact same point each sampling day.

The winter of 2019-2020 was very dry and cold and there was little snow on the ground. Some sampling sites were accessible during the campaign, some partly, and some had to be abandoned as the snow cover disappeared during a strong wind event.

To avoid contamination of the samples, snow sampling was done away from traffic patch of snow mobiles. If it was necessary to use a snow mobile to the sampling site, the snowmobiles was parked at least 50 meter upwind the site.

During sampling, clothes were covered with an overall suit, and hands was covered with disposable plastic gloves see Figure 3. For trace element analyse, two 50 mL vials (one each for CNR and NILU) were sampled for each sampling depth. For BC analysis, one large plastic bag (4-5L of snow which correspond to 2-3L melted water) was sampled. Similarly for POP approximately 4-5 L was sampled in either plastic bags or glass jars, and melted slowly at room temperature. Once melted the water was stored in a glass jar or in the plastic bottles, and stored at 4 degrees C. More details on how the sampling was performed is found in Annex B.

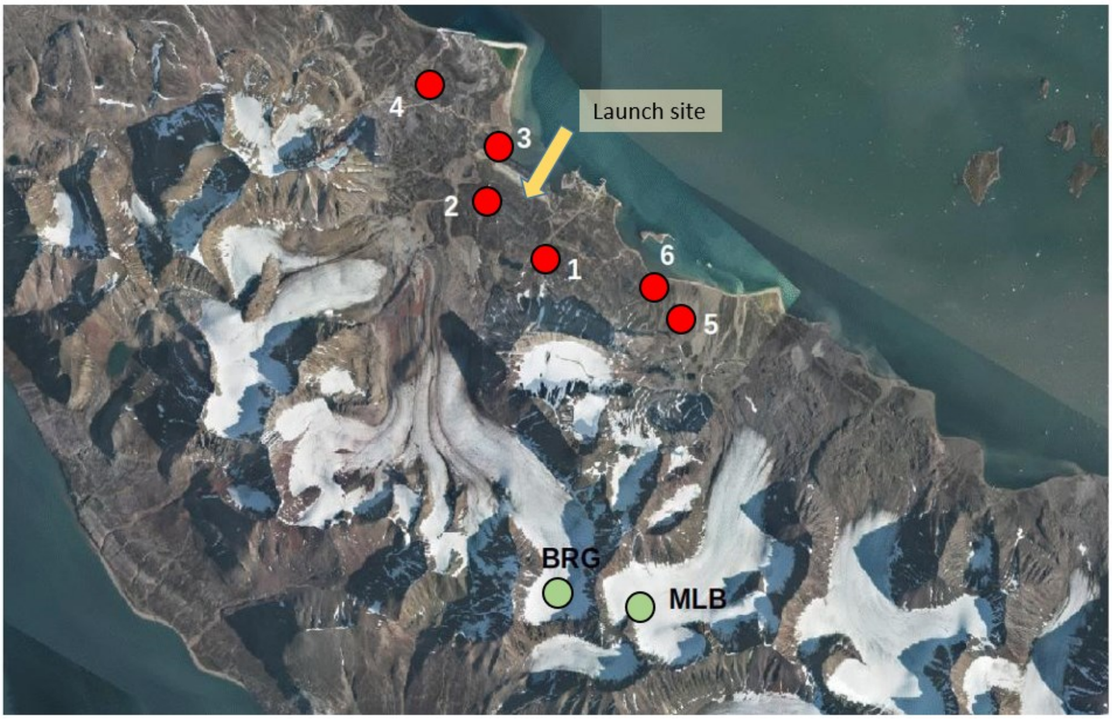

Figure 2: *Image with the location of the sampling areas. Red points (white labels) 1 to correspond to the winter samples. Green points (black labels) BRG and MLB are spring samples.*

Figure 3: NPI staff taking snow samples in winter 2019. Photo: Helge T. Markussen (NPI).

2.2 Overbank sediments in Brøggerdalen

Samples of overbank sediments from the two impact areas of the rocket boosters were collected during 21st and 22nd of August 2020. Samples were collected near fragments from the booster debris. The upper 2 - 3 mm of overbank sediments were collected by using a pre-cleaned shovel and transferred directly to the sample bags. Sample locations are indicated in Figure 4. Two samples were taken from booster impact area 1 (78° 54.59’N, 11° 49.41’) which was analysed separately, two samples from booster impact area 2 (78° 55.33’N, 11° 49.43’E) was collected and analysed as a pooled sample, and one sample from a reference point (78° 54.61'N, 11° 49.40'E, 25 meters from impact area 1) was collected and analysed. All the samples were analysed at Eurofins Environment Sweden AB for trace elements (ISO 17294-2:2016), PCBs (EN 16167), PAHs (ISO 18287:2006-05), BTEX (EPA 5021) and selected aliphatic/aromatic compounds (SPI 2011 and TEK353N012).

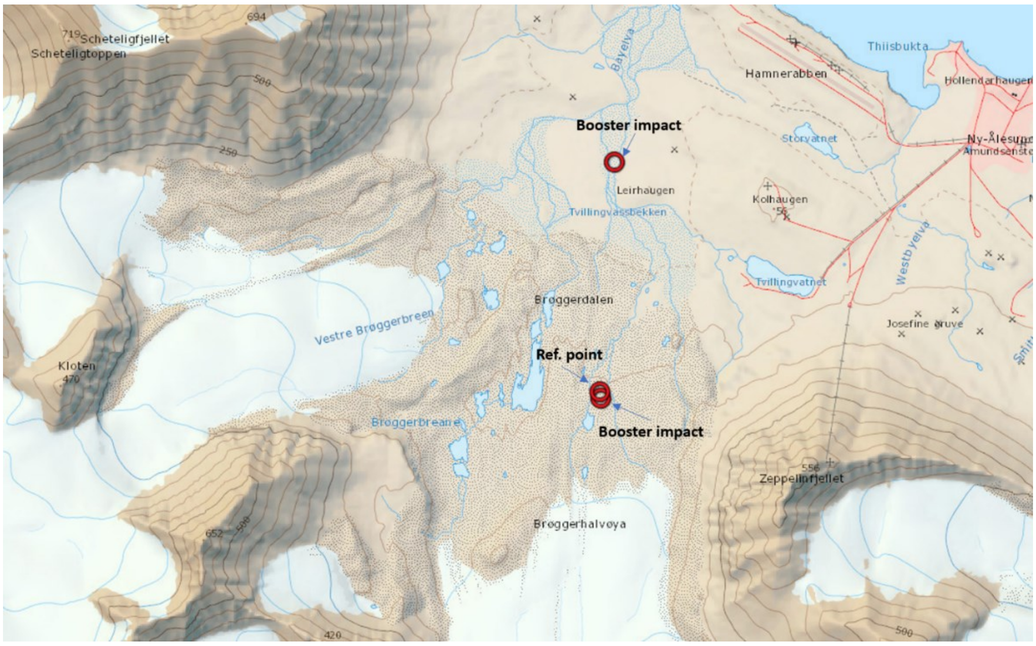

Figure 4: Sample locations (red circles) for overbank sediments from impact areas and reference point in Brøggerdalen

2.3 Atmospheric observations

The Zeppelin Observatory (78°54'26"N, 11°53'12"E, 474 m a.s.l.) on the Zeppelin mountain is location to several long-term monitoring programs, including the Norwegian air monitoring program by NILU and observations of aerosol properties by Stockholm University (SU). Observations from these programs were checked to assess whether they were impacted by the rocket launch.

The concentration levels during the launch were compared to long term data on aerosol properties, climate gases, hydrocarbons and POPs. Details of these measurements are found in annual reports of contaminants (Nizzetto et al., 2020), inorganic compounds (Aas et al., 2020) and aerosols properties and climate gases (Myhre et al., 2020).

Long term observations of atmospheric composition and aerosol properties are also conducted at Gruvebadet (78°55'07"N, 011°53'30"E, 40 m a.s.l) by CNR-ISP.

2.4 Analytical methods

The trace elements was analyzed both at NILU and at CNR-ISP with ICP-MS instrumentation, more details of the analysis at CNR-ISP are found in Annex C while the analysis at NILU in Annex B and in Bohlin-Nizzetto et al (2020). Identification and quantification of the selected POPs was carried out using a HRGC/HRMS setup (Bohlin-Nizzetto et al., 2020).

Measurements for BC in snow was done by University of Perugia, Italy, using standard Sunset instrument and the standard temperature protocol adopted in Europe (EUSAAR-2).

The inorganic analysis of filter samples at the Zeppelin Observatory was done from water extracts of the filter pack samples analysed with ion chromatography (Aas et al. 2020), the aerosol absorption measurements was done using an AE33 aethalometer, particle number size distribution in the range of 0.01 – 0.8 µm was measured using a Differential Mobilty Particle Spectrometer (DMPS), and carbon monoxide (CO) is monitored using a Picarro Cavity Ring-Down Spectrometer for continuous measurements, Myhre et al. (2020).

3 Results

3.1 Meteorological conditions

It is important to evaluate the results in light of the meteorological conditions before, during and after the rocket launch and the time of sampling. Especially important is to know when the last fresh snow fell before the sampling, and the wind direction and speed to evaluate where potential deposition may have occurred. Meteorological data was collected from Norwegian meteorological institute in Ny-Ålesund during both launch periods are seen in Figure 6 (precipitation, snow depth and temperature) and in Figure 7 (wind speed and direction).

Before the launch 7 Dec 2018 it was a small snowfall, but the snow thickness before and during the launch was thin and it was difficult to sample enough snow for analysis without getting soil dust etc. in the sample. A new snow fall at 11 Dec 2018 came after the last snow samples were taken (8 Dec). During snow sampling it was hardpacked snow, but one tried to samples where it was more «loose» snow. The wind direction during launching was around 360 degrees, both at the ground level and at 474 m a.s.l. where the Zeppelin Observatory is located, Figure 7. The plume comes from north to south, and since the Zeppelin Observatory is south from the launch site, the rocket launch has potential to impact these air measurements. Snow samples from Knudsenheia/Lysbua was not taken after the launch since this was located north of the airport and probably not affected. It is expected that Gruvebadet, Zeppelin Observatory and Kolhaugen would have highest potential for receiving deposition, but maybe also at Nilsebu/Bayelva which is closest to the launch site.

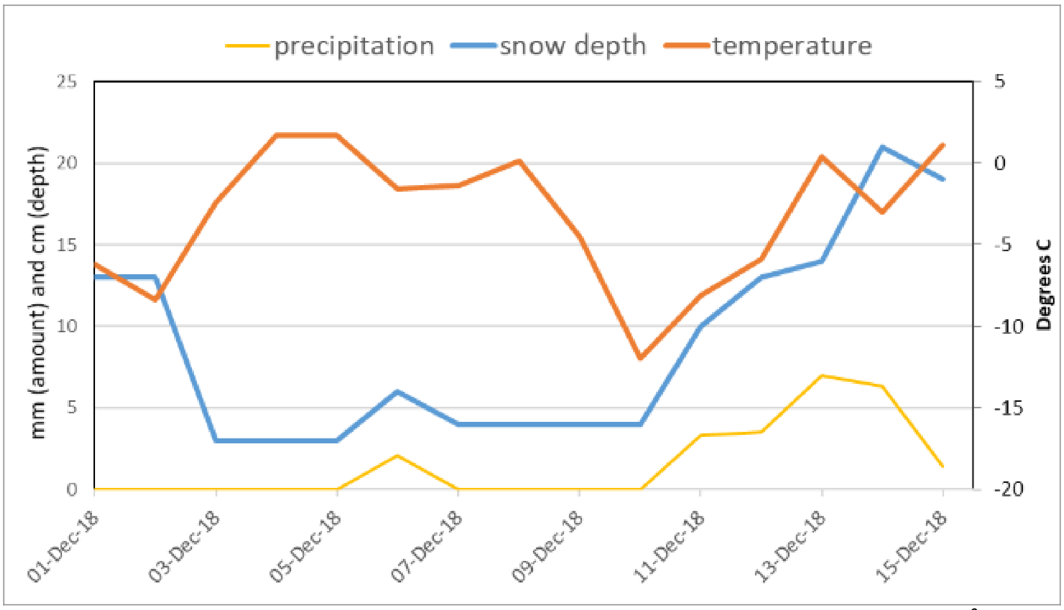

Figure 5: Precipitation, snow depth and temperature in Dec 2018 in Ny-Ålesund. Data from meteorological Institute downloaded from Norwegian meteorological institute (https://seklima.met.no/observations/)

During the second launch periods, in November and December 2019, it was some fresh snow falling just before the first rocket launch the 26th and then dry for the rest of the period, Figure 6.

The 2019 meteorological data was also taken from balloons launched just after the launch to further to assess where deposition may be expected. Figure 8 show the weather data (simplified, and only below 3 000 m a.s.l.), just after the launch on the 26 Nov and 10 Dec.

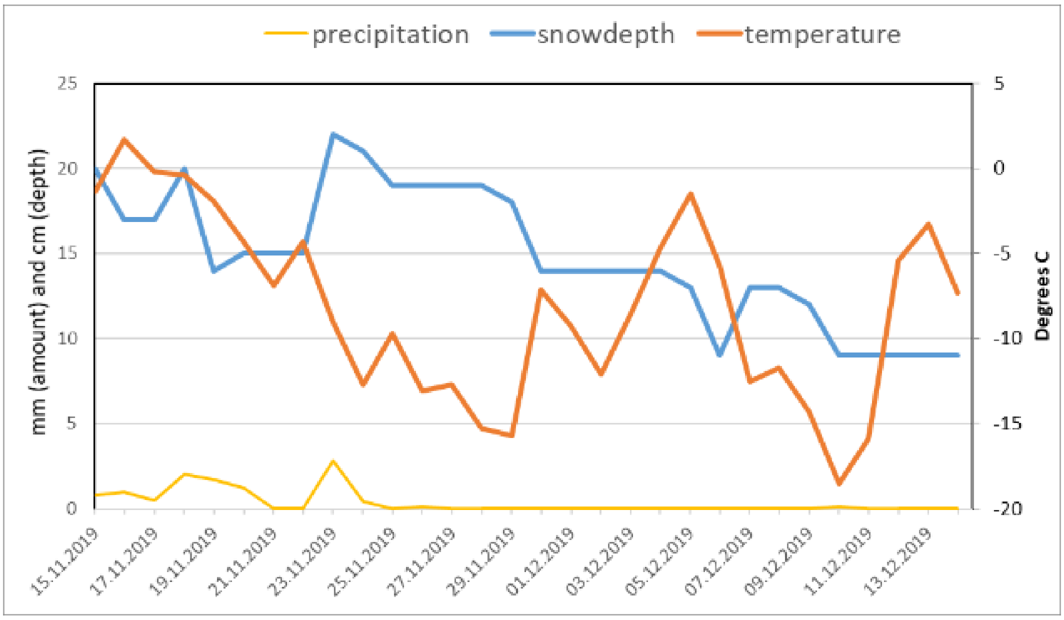

Figure 6: Precipitation, snow depth and temperature in Nov- Dec 2019 (bottom) in Ny-Ålesund. Data from meteorological Institute downloaded from Norwegian meteorological institute (https://seklima.met.no/observations/)

On 26 Nov 2019, the wind direction at the ground and at Zeppelin Mountain was 140-150 degrees, Figure 7 (middle), which is also seen from the balloon data up to around 1000 m a.s.l. The wind direction changed to 360 degrees above 1000 m a.s.l. Figure 8. In other words, the plume is pushing towards north at ground level and back towards west and then south in the upper level. Since the rocket is going very quickly at very high altitude, and is launched with a 85 deg. vertical angle, it is likely the first few seconds of the emission from the rocket is the main contributor. On the 26 Nov, wind pushing to the north direction at the ground level is then the main direction of the plume, meaning towards site 4 and further north towards the open fjord. Site 4 was unfortunately not sampled, but site 3 have also the potential for being affected.

On 10 Dec 2019 at 08.00 UTC, the wind was varying more with altitude. At the ground it was around 200 degrees while at Zeppelin mountain around 360 degrees, Figure 7 (right), which is also seen from the balloon data. Above 500 m a.s.l., the wind directions shift steadily towards 250 degrees, Figure 8. Thus, the plum was pushed over a West-East radius around the launching site, with the following sequence: West-North-West-East-North.

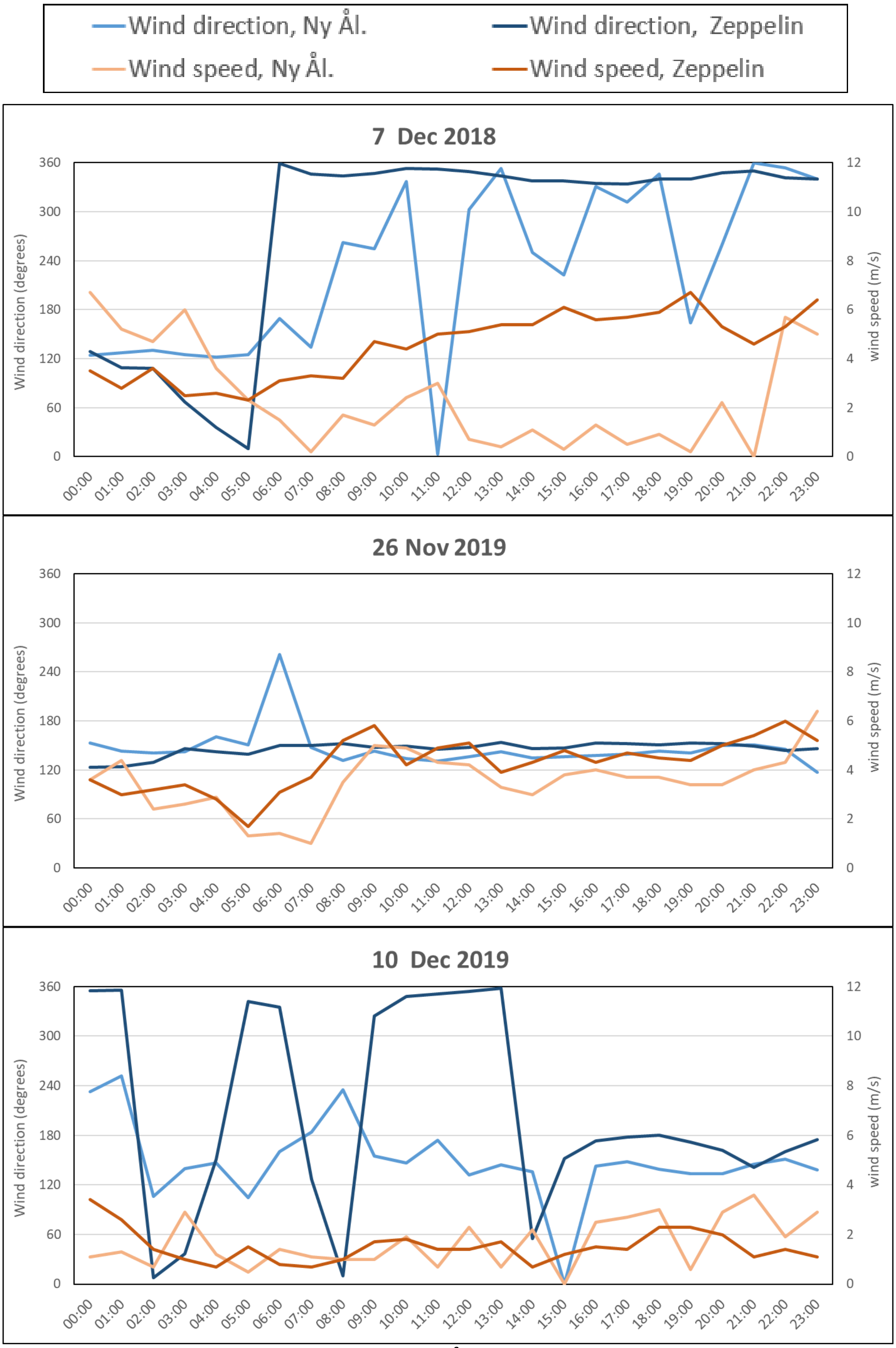

Figure 7: Wind directions and speed during in Ny-Ålesund the days of the rocket launches. Hourly averaged data from Ny-Ålesund are from the Norwegian meteorological institute (https://seklima.met.no/observations/), while the data from Zeppelin is from NILU (http://ebas.nilu.no/).

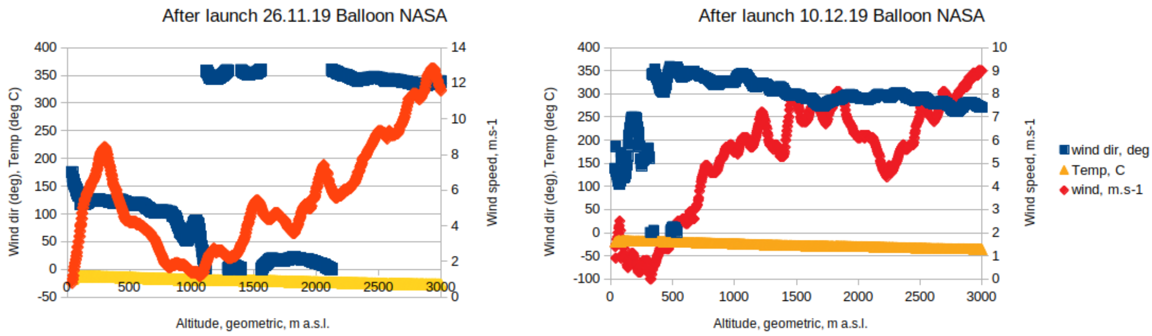

Figure 8: Simplified Meteorological data just after the rocket launched 26 Nov 2019 (left) and 10 Dec 2019 (right) from a weather balloon (data, courtesy of NASA).

3.2 Snow samples in December 2018

All the results from the snow samples are found in the Annex Table A.3 for trace elements and Table A.6 for POPs. The prevailing wind direction should if significant emissions from the rocket, cause higher deposition at the snow sampling sites south of the launch site. This is not the case, it was a large variability in the results, even very large differences between samples from the same location taken at the same time. To easier assess whether there were any changes in the concentrations of trace elements, all the snow samples for each sampling date was averaged. The POP analyses were done on pooled samples and not possible to distinguish between sampling sites. Figure 9 shows the average concentration of the trace elements measured above the analytical detection limits, samples before, just one day after the launch. There is no detectable change measured in any of the trace elements measured by NILU, but the snow sampling conducted in Ny-Ålesund by CNR-ISP showed indication of increase in Al in the surface snow layer 7 to 10 hours after the launch (data not shown).

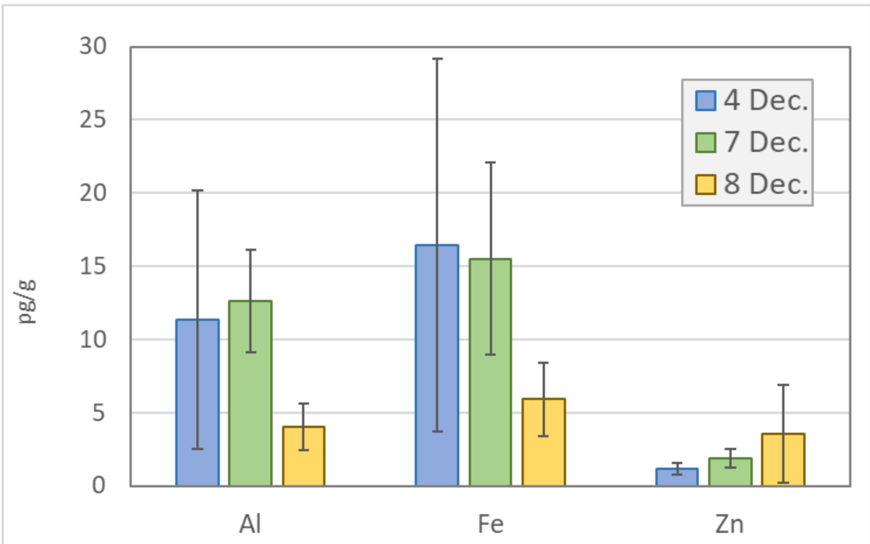

Figure 9: Average concentrations and the standard deviations from all the snow samples (from Table A.2) of Al, Fe and Zn before (4 dec), day of launch (7 dec) and after (8 dec) the launch.

Most of the POPs measured where below the detection limit, Table A.4. The average concentrations of the sum of the different groups of POPs (dioxins, furans and non-ortho (dioxin-like) PCBs) is shown in Figure 10 as well as the average concentration for PCB-77 and PCB-81 which were the only two components detected above the detection limit. There seems to be an increased level at the day of the launch, especially for the two dioxin-like PCBs. It is difficult to know if this is due to the rocket launch, though there are possibilities that dioxin like compounds can be formed during the combustion. The uncertainties in the results are however high and it is difficult to interpretate due to lack of historic data.

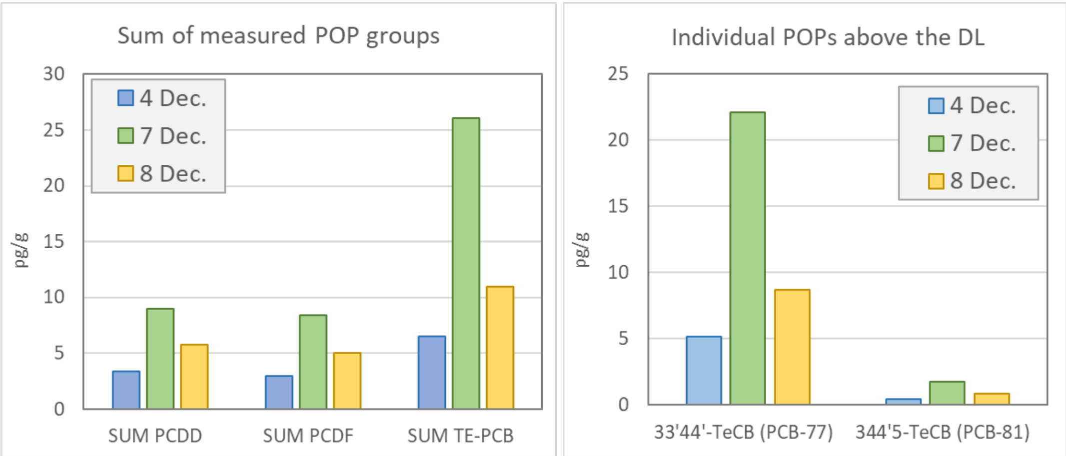

Figure 10: Average concentrations from all the snow samples of the sum of dioxins (PCDDs), furanes (PCDF) and non-ortho-PCBs (TE-PCB's) in the left figure while the two individual POPs which are measured above the detection limit is given at right. The averages are representing the concentration before (4 dec), the day of launch(7 dec) and after (8 dec) the launch.

3.3 Atmospheric observations in December 2018

Measurements of aerosol size distribution are done for all types of aerosols, in addition a subset of these aerosols where measured where one has applied heating do evaporate the volatile aerosols, thus measuring the size distribution of non-volatile aerosols, or solid aerosol. In Figure 11 size distribution of these two datasets are shown. It seems like there is some new particle formation of solid aerosols at time of rocket launch, this is shown as an increased concentration in small aerosols (small particle diameter). This is detectable only for a short period. The relative high concentrations at higher size binds (larger particle diameter) a bit after the launch is due to long range transport of air pollution from areas outside Svalbard. There is also an increase in carbon monoxide (CO) just after the launch (Figure 12), but it is not necessary due to the combustion of the rocket fuel. Most likely not, as there is no significant changes in the aerosol absorption concentrations during rocket launch, even though some enhancement is seen in these observations as well Figure 12.

For the other measurements at Zeppelin Observatory, there was not seen any visual impact on the concentration levels. If there were large emissions of ammonium from the fuel, which consist of ammonium perchlorate, and this has reached the Zeppelin Observatory that may influence the ammonium observations. However, the daily data (see Table A.5) reveal no detectible effects. Unfortunately, the ToF-ACSM was not in operation during this period, this instrument has high resolution observation of ammonium and other inorganic ions as well as organic aerosols. Other data are found in http://ebas.nilu.no/.

Even though the impact on the measurements at the Zeppelin Observatory is relatively low, it is recommended that online data should be flagged in the hour at the launch time to avoid that these data are used without caution.

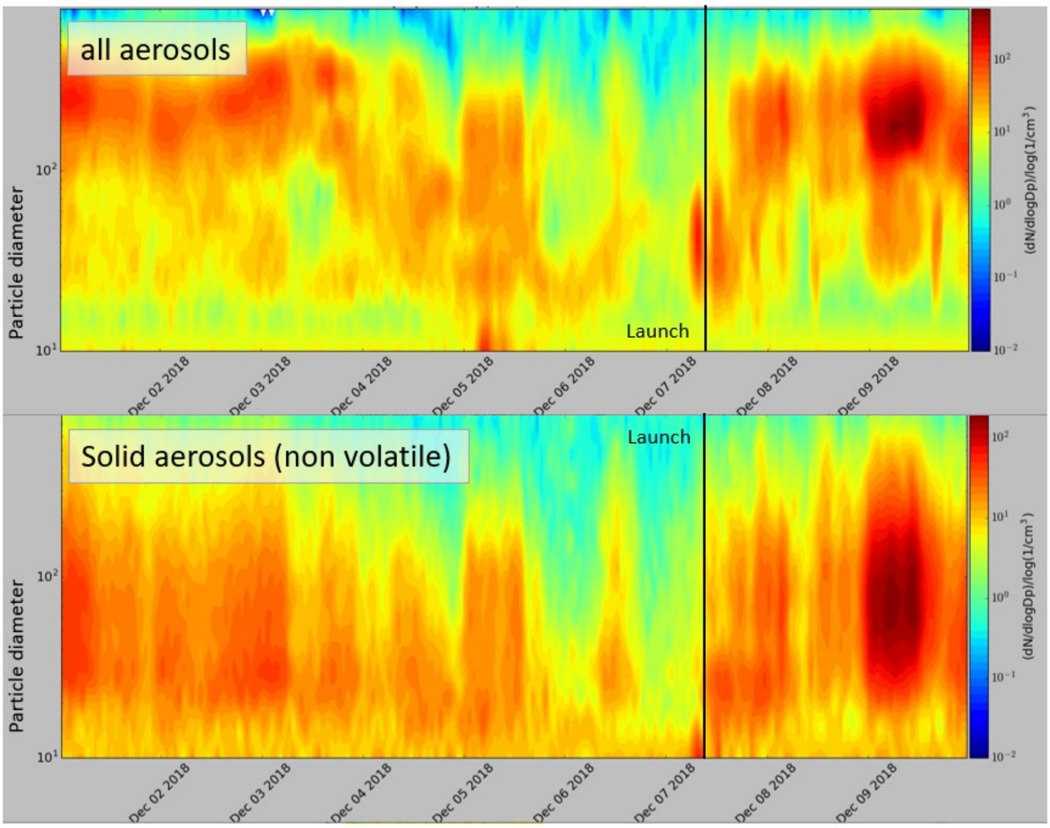

Figure 11: Observations of aerosol size distribution of non-volatile 1-9 December 2018

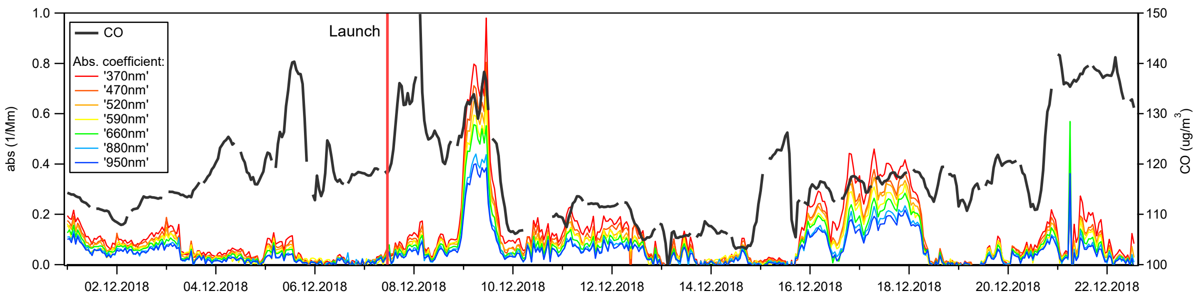

Figure 12: Observations of carbon monoxide (CO) and aerosol absorption at different wavelength at Zeppelin in December 2018

In Gruvebadet there are aerosol observations by CNR-ISP, and it was very small enhancement in the aerosol absorption coefficient (by the PSAP instrument) just at the launch, but it is does not significantly impact on the observation that day (7 Dec).

3.4 Trace elements November-December 2019

Snow samples were analysed for trace elements both at NILU and CNR-ISP. The individual results for all the samples are found in the Annex, Table A.6 shows the data from NILU.

The datasets are presented a bit differently. The trace elements analysed at NILU are averaged into for different periods. Before and just after the 1st launch the 26th of November and before and after the 2nd launch the 10th of December. Only samples from sites 1-3 were averaged since these were closest to the launch site and expected to get highest impact, but samples from different snow depth were not distinguished since it was not a clear systematic difference from which layer the samples were taken from, Table A.6. The average concentrations of the element above the detection limit are shown in the trace elements analysed CNR-ISP were converted in flux (expressed in mg per m^2 of ground) to avoid bias from differences in snow density. Figure 14 presents the flux of Al and Fe, as being the two most pronounced peaks in the data, and the main component of the fuel used.

The two first sampling days (21 and 24 November) show the background values. After the first rocket launch, a strong peak in Fe and a very strong one in Al is observed at site 3, which is the closest to the launching pad. Same is seen in both datasets (Figure 13 and Figure 14). If one takes out this specific sample the average Al concentration is not much higher than the background level.

The Al values returned to lower values quickly after, close to background for site 3, but higher for the other sites. Reasons are likely due to the wind remobilizing the thin and loose snow (on 27 and 28-29 November, strong wind was observed coming from the fjord and towards the ocean, blowing snow away from town). The reasons for site 3 keeping on constant higher background values is probably due to its location, i.e. below the airport, and likely more exposed to wind deposition of blowing dust and/or activities of trucks and airplanes at the airport facilities.

The second launch occurred on 10th of December, it was observed a very strong peak but only for Fe at site 2, very close to the launching area. The following day on 11th December, all accessible sites were sampled, and showed higher concentration than the initial background in Fe and Al, apart from site 3. Zn does not show any significant differences between the snow samples during the period, Figure 14.

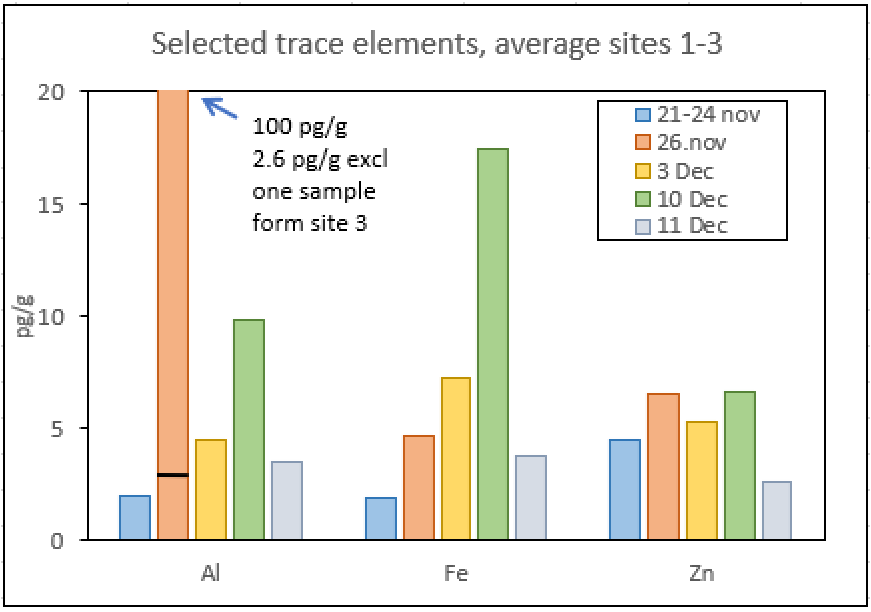

Figure 13: Average concentrations of Al, Fe and Zn of all snow samples from sites 1-3 before, between after the two rocket launches (26. Nov and 10 Dec).

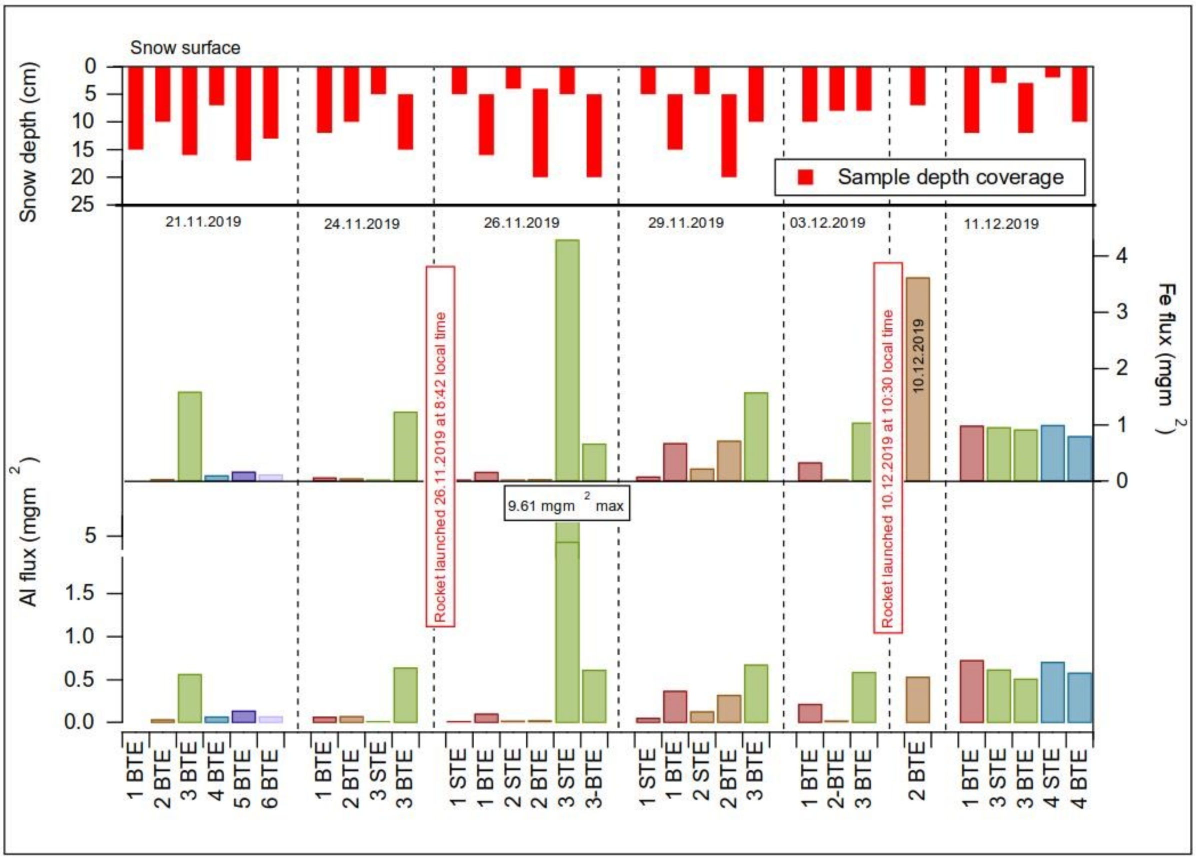

Figure 14: Plots of the surface sample results taken in winter 2019, for Al and Fe, and as a function of samples depth. The 3 STE samples peaks at 9.61 mg m^{-2}.

In short, the surface samples show that there is likely deposition of trace elements due to the rocket launch, but each rocket launch did not have the same effect on the snow surface concentration. The second launch had a more pronounced effect in terms of deposited particles at all sites. Unfortunately, after the first wind storm, we had no more access to sites 5 and 6. The first launch strongly impacted site 3, and that site seemed to be already naturally quite loaded.

It is difficult to firmly conclude on the annual contribution of the loading in terms of trace elements at ground points because the i) snowpack was very thin during the sampling and ii) the wind has remobilized a lot of the snow, mixing and merging the snow layers where potentially the particles have been deposited on. We also lack background data in these areas.

3.5 Organic contaminants in snow, November-December 2019

Similarly to 2018 data, most of the POPs measured where below the detection limit Table A7. Figure 10 shows the average concentrations of the sum of the different groups of POPs (dioxins, furans and non-orthoPCBs), and there is an indication of increased sum of dioxins (PCDDs) after the launch 10 Dec. One sample at site 1), but whether this is due to the launch is difficult to conclude since the uncertainty is too high.

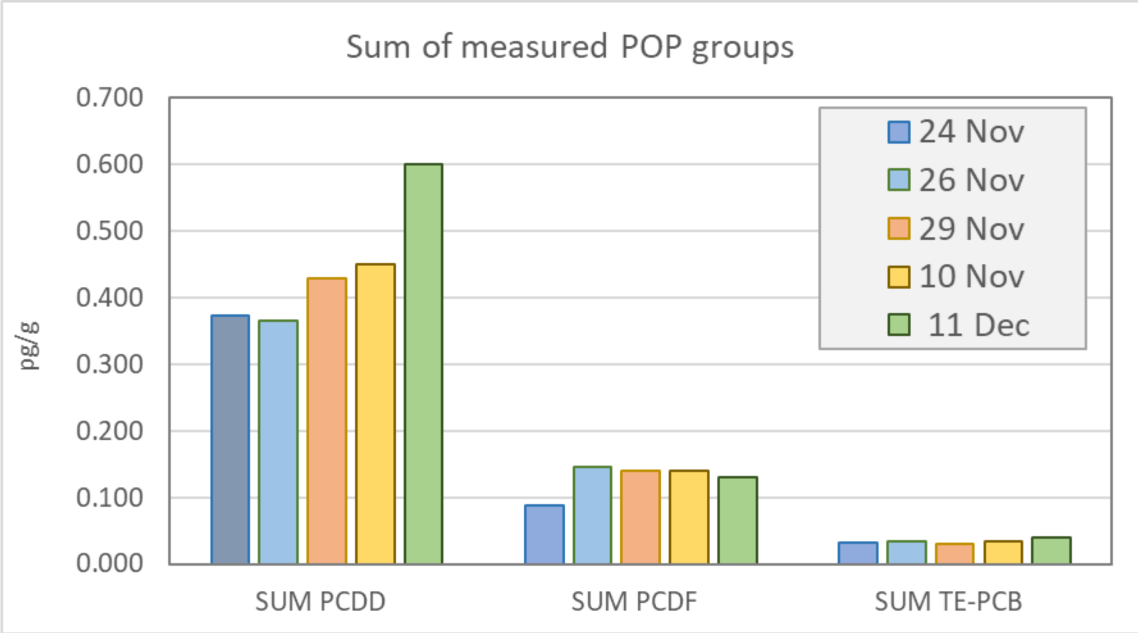

Figure 15: Average concentrations from all the snow samples of the sum of dioxins (PCDDs), furanes (PCDF) and non-ortho-PCBs (TE-PCB's) of all snow samples from sites 1-3 before, between after the two rocket launches (26. Nov and 10 Dec).

3.6 Black carbon in snow, November-December 2019

The BC results from the 2019 snow samples showed all a concentration of below 2 ng/g, with only 6 samples out of 26 having a detectable value. The values are well in the range of the background, and we cannot attribute the small value to the launch.

3.7 Atmospheric observations, November-December 2019

The observed aerosol size distribution both solid and non-volatile aerosols at the Zeppelin Observatory before, during and after the two rocket launches in 2019 are seen in Figure 17, while observations of CO and aerosols absorption is found in Figure 16. At the launch 26 Nov it is very little pollution, the 10 Dec on the other hand there is an ongoing pollution episode and it is difficult to evaluate whether the rocket exhaust cause any additional impact. There is not any new particles formed Figure 17, but there are larger aerosols with a small enhancement just after the launch, but this can be part of the ongoing long range transported episodes. For the other observations at Zeppelin there were any detectible impact on the concentration levels.

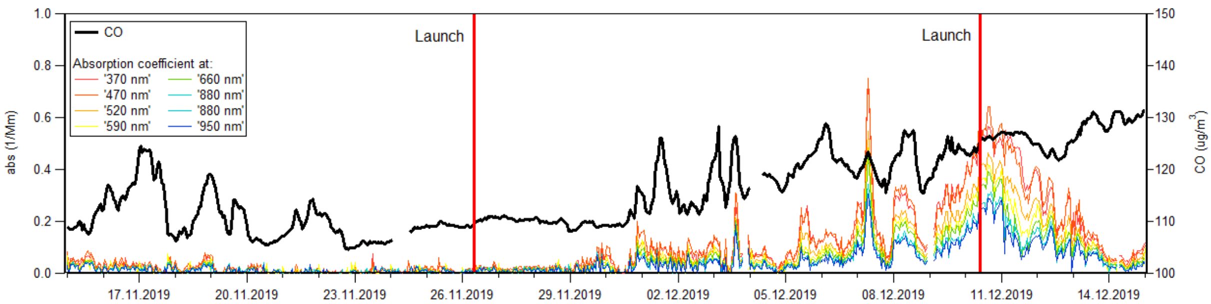

Figure 16: Observations of CO and aerosol absorption at different wavelength at Zeppelin from 15 November to 15 December 2019.

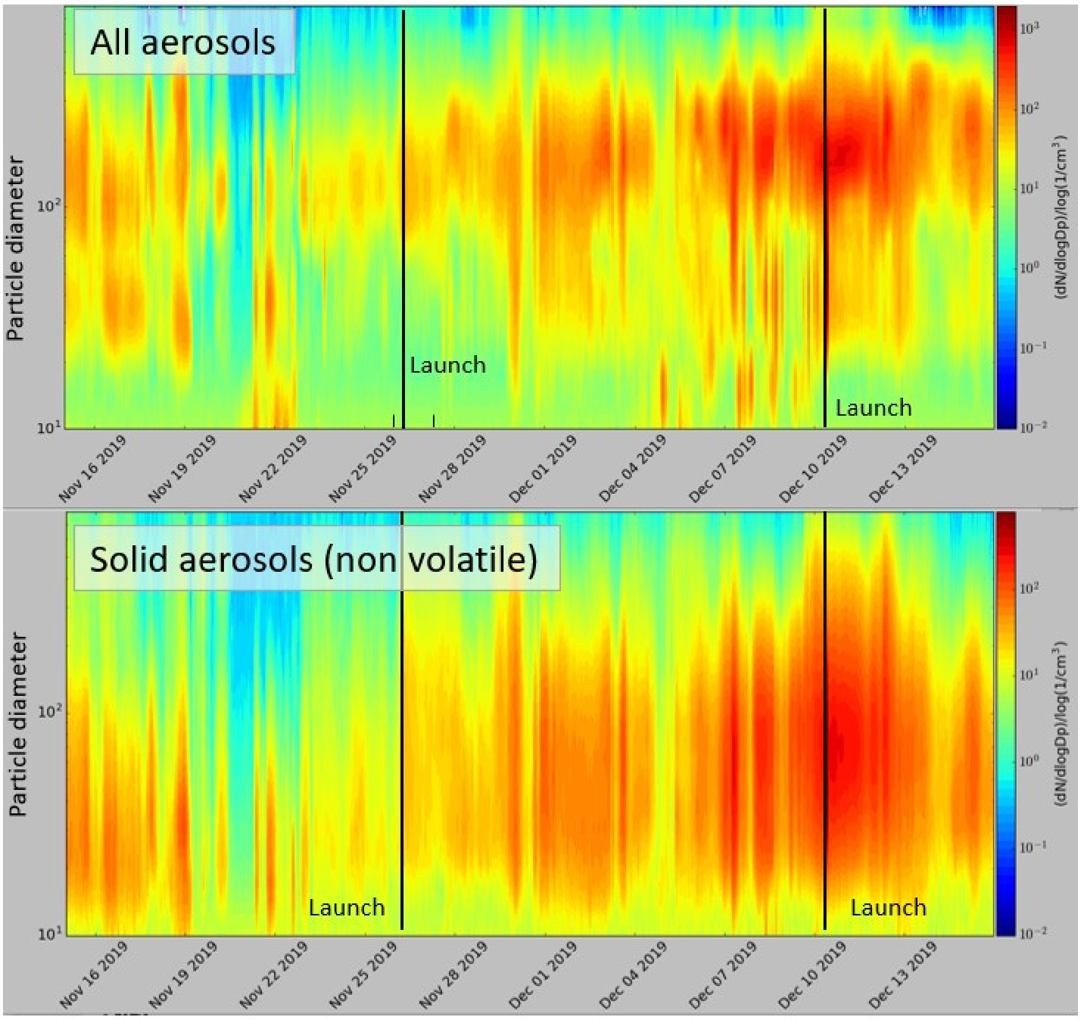

Figure 17: Observations of aerosol size distribution at Zeppelin Observatory, 15 November to 15 December 2019

3.8 Trace elements from snow samples on glaciers 2017-2020

Compared to snow sampling, it is a more robust method to use the glaciers data since:

1. We have access to background levels (data from spring 2017 and 2018, two years without rocket launch).
2. The glaciers are oriented differently to the main wind direction during the sampling period, and were then more protected, prevailing the snow to be blown away
3. Precipitation, the amount of snow deposited on the glacier, is higher at the glaciers than at ground level, and the snow layers where potentially particles are deposited are more quickly buried by the new and fresh snow, and consequently the signal is much better preserved.

These two points BRG and MLB in and denote two local glaciers we used to monitor snow for trace elements, a collaborative project between NPI and CNR. Figure 18 shows the results we obtained on the two glaciers, in terms of deposition fluxes (mg m-2) and normalized ratios with Zinc (Zn). Fluxes results show large variability and higher values for Fe than Al. Sources of both are either natural (Earth's crust), i.e. dust event (long range or local transport) but these two are the main components of the rocket fuel. This is the reason why we only focus on these two elements. Comparing only the fluxes is not evident as we cannot determine if a peak is natural or not. Instead, we are using normalized ratios with Zn. Reason is that Zn is very stable and has very few natural sources, which is not the case of Al and Fe. It is then expected when working with ratios that these numbers are rather stable over time. Even if the Fe fluxes are larger, its ratio with Zn remains stable when the contribution is from natural emission, meaning the source is likely for the upper crust of the Earth. We know the constitution of the Earth crust but only on average. This is why the ratios can deviate from 0 to 2, depending on the exact constitution (or origin) of the deposited material. Al ratio with Zn behaves in the same way. Now, when the ratios are > > 2, it might indicate contamination, meaning a source which is different from the average Earth crust composition, and not natural or with a very atypical constitution (volcano eruption, strong pollution event).

Figure 18 show the normalized ratio of Fe and Al, as well as the fluxes, respectively for BRG and MLB. As expected, the 2017 and 2018 data (orange and red backgrounds) are below 2 in general, except at the beginning and end of the season. The start and the end of the snow season is always particular as it can be quite some of the ground still non snow cover, contributing to dust source for the glaciers, as well as melting and concentration of the element in the ice matrix. Once the snowpack is in place in Ny-Ålesund, mainly long range transport should contribute.

The results from 2019 reveals that elevated levels of trace elements especially Al from BRG. Figure 18 shows several peaks for the start of the season, but the normalized Zn ratios are not behaving the same for Al and Fe which means the signals are not fully synchronized as it should be for a very local pollution event like a rocket launch. At about 45-50 cm depth in the glacier, we have a large Al and marked Fe synchronised peaks for both elements, likely associated the rocket event. ***The total contribution of the launch in 2018 estimated in terms of mass percentage is 11% for Fe and 20% for Al on BRG in 2019, compared to the annual load that year.***

On MLB, synchronised peaks between Fe and Al are observed at 35-40 cm height, and it is well more marked for Al. ***The estimated total contribution of the launch in 2018 is 6% for Fe and 15% for Al on MLB***. In 2019, BRG has been more exposed than MLB. One reason is that the rocket is launched just over the glacier but difficult to confirm without any meteorological data from on site.

The results from 2020 show that on BRG, two synchronized peaks are seen at 30 cm height, small for Fe and a bit larger for Al. ***The total contributions from the launch in 2019 are 12 % for Fe and 14 % for Al on BRG in 2020***. It can be noticed that in 2020 the fluxes are in general much lower than in 2019 on that glacier. On MLB, two synchronized peaks are seen at 35-40 cm height, higher in amplitude for both elements. ***The total contributions from the launch in 2019 are 27 % for Fe and 25 % for Al on MLB in 2020***.

Comparing the years 2019 and 2020 (pointing back to the rocket launches in 2018 and 2019, respectively), BRG has been more affected by the launch in both Fe and Al, while MLB has been more affected in 2020. Looking at Figure 18, winds during the launch were pushing the plume at ground level either towards the North and the fjord for the first rocket, or around and West-East radius for the second one. The ground level winds were more unstable during the second launch, while the first one probably directed most of the low elevation emission out towards the fjord. For the second launch, it is likely the plume at slightly higher altitude contributes to the deposition since MLB is further away from the launching site.

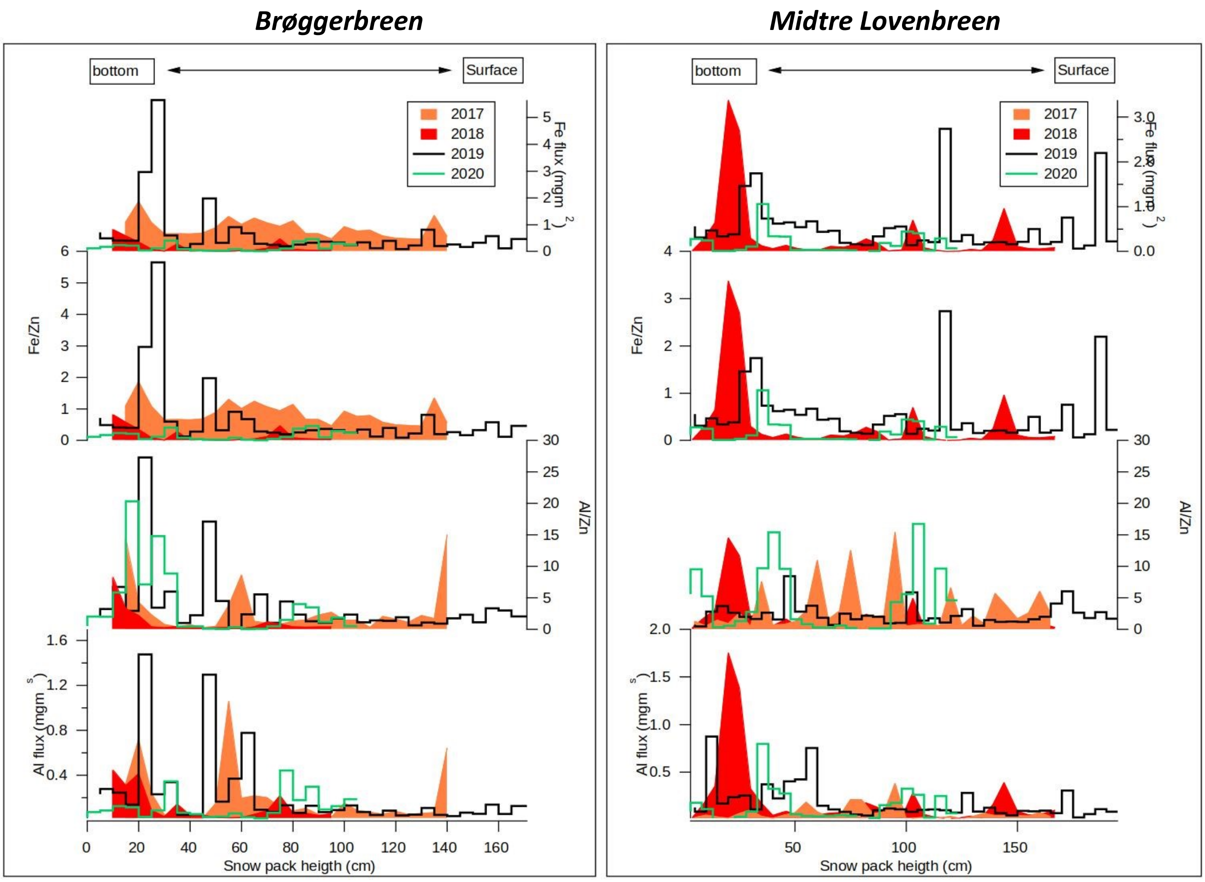

Figure 18: Fluxes of Al and Fe and fluxes ratio normalized with Zn for Brøggerbreen (left) Midtre Lovenbreen (right) from 2017 to 2020. 0 is the snow ice interface. The Y scale is not the same for Al and Fe.

3.9 Results from overbank sediments in Brøggerdalen 2020

Typical booster debris observed in the impact areas can be seen in Figure 19, and included scrap metal from the booster housing, insulation material, electric contacts etc. Some debris had the size of several centimetres (largest parts was scrap metal from the booster housing with dimension in the range 15 x 30 cm), while a larger fraction was smaller than 1 cm.

Figure 19: Booster debris observed within the impact areas. Photos: Øyvind Mikkelsen, NTNU.

Table A.9 in Appendix A reports the results obtained from the overbank sediments from the booster impact areas in Brøggerdalen as well as the background point. Samples in the impact areas were taken near fragments from the boosters' debris. Overall, low concentrations were found of the analyzed trace metals, and PAHs as well as BTX and selected aliphatic/aromatic compounds were not detected above limit of quantification. However, in one location from impact area 1 (78° 54.59'N, 11° 49.41'E) elevated levels of cadmium (80 times higher than background) and presence of PCB138 was observed. The concentration of cadmium is relatively high also in the two other sample locations in the impact areas compared to the reference point and previous samples of overbank sediments in the upper part of Brøggerdalen (Kveli et al., 2015).

In general, there is also higher levels of copper and zinc compared to background observed in all the sample locations from the impact areas. The observed PCB138 congener is a relatively heavy PCB that is not likely explained by long-range atmospheric deposition. Origin could be from insulation material from the booster systems, but also other sources are possible. PCB138 has to our knowledge not been observed in the actual sample area before, however other heavy PCBs congeners (e.g., PCB180) have been observed in areas around Ny-Ålesund and potentially linked to migratory birds (Aslam et al., 2019). A recommendation is to test insulation materials used in the booster / rocket system for relevant PCBs. It's also important to stress that number of samples are low (4 samples), so any clear conclusion is not possible. Background levels were found in the reference point approx. 25 meters from the impact point, indicating limited spread. Largest concern is the presence of small fragments that cannot easily be removed. These might over time break up in even smaller fragments, mix up in the soil/water system and potentially end up in the local food web.

4 Discussion and Conclusion

The snow samples are difficult to interpret due to large variability in the data, which is especially a problem when discussion low concertation level in the polar environment. Specific measurements campaign collecting snow samples during the launches in 2018 and 2019 in Ny-Ålesund analysed for various contaminants showed the following results,

- Trace elements in 2018: there is no detectable change measured in any of the trace elements measured by NILU, but the snow sampling conducted in Ny-Ålesund by CNR-ISP showed indication of increase in Al in the surface snow layer 7 to 10 hours after the launch
- POPs 2018: increased concentration of two chlorinated organic pollutants after the launch, but it cannot be concluded whether it is caused by the rocket.
- Trace elements 2019: Significant impact of Al and to some extent Fe at a sites close to the launch. The second launch had a more pronounced effect. This is likely linked to the rocket launch, but the variability is high and it is difficult to be conclusive.
- POPs 2019: increased concentration of sum of dioxins after the second launch, but difficult to assess if this is due to deposition from the rocket.
- Black carbon 2019: No detectable effect

The samples taken on two small local glaciers (Brøggerbreen (BRG) and Midtre Lovenbreen (MLB) are easier to interpret than the snow samples on ground in terms of snow sequencing, and attribute the origin and timing of the deposition. Time series from 2017-2020 are analysed to assess the impact from the launches in Dec 2018 and Nov-Dec- 2019. The estimated total contribution of the launches compared to the annual deposition that year was estimated to:

- 11% for Fe and 20% for Al on BRG due to the launch in 2018
- 6% for Fe and 15% for Al on MLB due to the launch in 2018
- 12 % for Fe and 14 % for Al on BRG due to the launch in 2019
- 27 % for Fe and 25 % for Al on MLB due to the launch in 2019

For the atmospheric measurements at the Zeppelin Observatory , there is a detectable influence on the size distribution measurements where formation of solid aerosols was caused by the launch in December 2018 It was also seen a small enhancement in the aerosol absorption coefficient at the Gruvebadet Observatory just at the launch in 2018. In 2019 it is not documented any changes which one can conclude was due to the rocket launch. Even though the impact on the atmospheric measurements are low, it is recommended that online data should be flagged in the hours around the launch to avoid that these data are used without caution.

Debris from the booster rocket including scrap metal, insulation material, electric contacts were observed in Brøggerdalen, and there is indication that this may have caused contamination in the overbank sediments.

5 Acknowledgements

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Appendix A

Observations from snow and air samples

Table A.1: Location of sampling sites during December 2018 and sampling dates at these sites

Sample sites	Coordinates	Date	No. of samples
Zeppelin	N 78 54.430	20181204	2 (appx 5m apart)
	E 011 53.180	20181207	2 (appx 5m apart)
Gruvebadet	N 78 55.029	20181207	2 (appx 5m apart)
	E 011 53.797	20181208	2 (appx 5m apart)
Kolhaugen	N 78 55.197	20181204	2 (appx 5m apart)
	E 011 51.009	20181208	2 (appx 5m apart)
Nilsebu/Bayelva	N 78 55.873	20181204	2 (appx 5m apart)
	E 011 49.761	20181207	2 (appx 5m apart)
		20181208	2 (appx 5m apart)
Knudsenheia	N 78 56.421 E 011 50.208	20181204	2 (appx 5m apart)
Corbel	N 78 54.016	20181206	1
	E 012 07.220	20181208	1

Table A.2: Location of sampling sites for surface snow samples during November December 2019

Site nr	**name**	**latitude (N)**	**longitude (E)**	**Altitude**
1	Gruvebadet	78.91731	11.89626	43.1
2	Kollahaugen	78.92481	11.85167	20.6
3	Flypass Kysten	78.93233	11.85544	10
4	Knudsenheia	78.94019	11.80241	25.3
6	Ny-Ålesund Brua	78.91466	11.98361	3

Table A.3: Snow samples before and after launch in Dec 2018 analysed for trace elements. Numbers in yellow are data below detection limits while the ones in red are not used due to contamination (particles in sample). Unit pg/g.

Site	sample date	Al	Fe	Zn	Co	Ni	V	Cd	Pb	Cr	Cu
Zeppelin	04.12.18	7.16	11.62	0.88	0.012	0.06	0.02	0.006	0.04	0.09	0.05
Zeppelin	04.12.18	19.66	29.11	0.60	0.018	0.06	0.05	0.006	0.04	0.09	0.05
Corbel	06.12.18	1.00	0.70	0.63	0.008	0.06	0.02	0.006	0.04	0.09	0.05
Kolhaugen	04.12.18	52.19	75.19	0.60	0.049	0.11	0.12	0.006	0.07	0.09	0.05
Kolhaugen	04.12.18	4.09	6.43	1.06	0.009	0.06	0.03	0.006	0.04	0.09	0.05
Knudsenheia/Lysbua	04.12.18	1.26	3.15	2.68	0.008	0.06	0.02	0.006	0.04	0.09	0.05
Knudsenheia/Lysbua	04.12.18	1.16	2.23	2.33	0.008	0.06	0.02	0.006	0.04	0.09	0.05
Nilsebu/Bayelva	04.12.18	4.13	3.24	0.60	0.008	0.06	0.02	0.006	0.04	0.09	0.05
Nilsebu/Bayelva	04.12.18	93.49	152.80	0.66	0.102	0.18	0.34	0.006	0.05	0.27	0.15
Zeppelin	07.12.18	5.09	7.34	0.96	0.015	0.06	0.03	0.006	0.04	0.09	0.05
Zeppelin	07.12.18	20.80	36.22	1.61	0.033	0.06	0.05	0.006	0.05	0.09	0.05
Gruvebadet	07.12.18	13.89	22.67	0.60	0.012	0.06	0.04	0.006	0.04	0.09	0.05
Gruvebadet	07.12.18	3.22	4.45	1.26	0.010	0.06	0.04	0.006	0.04	0.09	0.05
Nilsebu/Bayelva	07.12.18	18.18	2.37	2.93	0.011	0.06	0.02	0.006	0.04	0.09	0.07
Nilsebu/Bayelva	07.12.18	14.51	19.95	3.86	0.032	0.06	0.06	0.006	0.09	0.09	0.05
Gruvebadet	08.12.18	6.02	8.80	0.60	0.016	0.06	0.02	0.006	0.06	0.09	0.05
Gruvebadet	08.12.18	7.65	12.43	0.72	0.018	0.06	0.02	0.006	0.06	0.09	0.05
Kolhaugen	08.12.18	1.00	1.53	0.86	0.008	0.06	0.02	0.006	0.04	0.09	0.05
Kolhaugen	08.12.18	1.00	0.70	1.06	0.008	0.06	0.02	0.006	0.04	0.09	0.05
Bayelva	08.12.18	4.69	6.78	2.11	0.009	0.06	0.02	0.006	0.04	0.09	0.05
Bayelva	08.12.18	7.51	10.63	18.69	0.010	0.06	0.02	0.006	0.04	0.09	0.05
Corbel	08.12.18	0.50	0.45	0.65	0.008	0.06	0.02	0.006	0.04	0.09	0.05

Table A.4: Pooled snow samples before and after launch in Dec 2018 analysed for various POPs. Unit pg/g.

Compound		4 Dec.	7 Dec.	8 Dec.
Dioxins				
2378-TCDD	< DL	0.262	0.663	0.442
12378-PeCDD	< DL	0.447	1.13	0.753
123478-HxCDD	< DL	0.358	0.905	0.603
123678-HxCDD	< DL	0.362	0.916	0.611
123789-HxCDD	< DL	0.378	0.956	0.637
1234678-HpCDD	< DL	0.516	1.72	0.87
OCDD	< DL	1.08	2.73	1.82
SUM PCDD		3.403	9.02	5.736
Furanes				
2378-TCDF	< DL	0.198	0.571	0.334
12378/12348-PeCDF	< DL	0.211	0.832	0.368
23478-PeCDF	< DL	0.196	0.788	0.348
123478/123479-HxCDF	< DL	0.202	0.511	0.34
123678-HxCDF	< DL	0.202	0.511	0.34
123789-HxCDF	< DL	0.288	0.727	0.485
234678-HxCDF	< DL	0.226	0.571	0.381
1234678-HpCDF	< DL	0.261	0.661	0.441
1234789-HpCDF	< DL	0.308	0.854	0.519
OCDF	< DL	0.883	2.34	1.49
SUM PCDF		2.975	8.366	5.046
nonortho - PCB				
33'44'-TeCB (PCB-77)		5.14	22.1	8.66
344'5-TeCB (PCB-81)		0.433	1.72	0.848
33'44'5-PeCB (PCB-126)	< DL	0.656	1.66	1.11
33'44'55'-HxCB (PCB-169)	< DL	0.238	0.561	0.374
SUM TE-PCB		6.467	26.041	10.992

Table A.5: Daily mean concentrations of inorganic components measured at Zeppelin Observatory, Dec 2018. Unit $\mu g/m^3$.

sampling date	NH3-N	NH4-N	Ca	Cl	Mg	NO3-N	HNO3-N	K	NA	SO4-S ssc	SO4-S tot	SO2
01.12.2018	0.025	0.02	0.03	0.46	0.04	0.005	0.015	0.03	0.32	0.16	0.19	0.015
02.12.2018	0.025	0.005	0.04	0.27	0.03	0.02	0.015	0.04	0.2	0.11	0.13	0.08
03.12.2018	0.03	0.005	0.02	0.47	0.03	0.005	0.015	0.05	0.31	0.1	0.13	0.11
04.12.2018	0.03	0.005	0.02	0.2	0.02	0.02	0.015	0.03	0.16	0.13	0.14	0.11
05.12.2018	0.025	0.005	0.005	0.12	0.005	0.02	0.015	0.005	0.09	0.07	0.08	0.09
06.12.2018	0.03	0.005	0.005	0.04	0.005	0.02	0.015	0.005	0.04	0.07	0.07	0.09
07.12.2018	0.025	0.005	0.005	0.05	0.005	0.01	0.015	0.005	0.03	0.06	0.06	0.08
08.12.2018	0.025	0.005	0.02	0.68	0.04	0.03	0.01	0.02	0.43	0.07	0.11	0.07
09.12.2018	0.03	0.02	0.03	0.95	0.07	0.03	0.015	0.05	0.61	0.12	0.17	0.09
10.12.2018	0.03	0.005	0.01	0.46	0.03	0.02	0.015	0.005	0.3	0.07	0.1	0.13
11.12.2018	0.03	0.005	0.005	0.22	0.005	0.005	0.015	0.01	0.14	0.08	0.09	0.26
12.12.2018	0.025	0.02	0.04	1.33	0.1	0.005	0.015	0.04	0.76	0.08	0.14	0.08
13.12.2018	0.025	0.005	0.01	0.51	0.03	0.005	0.015	0.01	0.31	0.06	0.09	0.09
14.12.2018	0.03	0.005	0.02	0.81	0.05	0.005	0.015	0.02	0.48	0.05	0.09	0.09
15.12.2018	0.025	0.005	0.005	0.2	0.005	0.005	0.015	0.005	0.12	0.06	0.07	0.08
16.12.2018	0.06	0.02	0.01	0.34	0.03	0.01	0.015	0.02	0.24	0.12	0.14	0.08
17.12.2018	0.03	0.05	0.03	0.78	0.07	0.02	0.015	0.05	0.54	0.2	0.25	0.15
18.12.2018	0.03	0.005	0.04	0.18	0.04	0.02	0.015	0.04	0.3	0.24	0.27	0.5
19.12.2018	0.08	0.005	0.005	0.08	0.005	0.01	0.015	0.005	0.07	0.08	0.08	0.09
20.12.2018	0.025	0.005	0.005	0.01	0.005	0.01	0.015	0.02	0.01	0.07	0.07	0.015
21.12.2018	0.08	0.005	0.02	0.63	0.05	0.04	0.015	0.04	0.49	0.12	0.16	0.015
22.12.2018	0.03	0.005	0.01	0.15	0.02	0.03	0.15	0.02	0.25	0.16	0.17	0.015
23.12.2018	0.07	0.005	0.02	0.65	0.05	0.02	0.015	0.04	0.43	0.1	0.14	0.09
24.12.2018	0.06	0.01	0.02	0.37	0.02	0.02	0.015	0.03	0.24	0.1	0.12	0.015
25.12.2018	0.07	0.005	0.005	0.24	0.01	0.01	0.015	0.02	0.16	0.09	0.1	0.09
26.12.2018	0.07	0.005	0.02	0.29	0.03	0.01	0.01	0.03	0.19	0.11	0.13	0.09
27.12.2018	0.11	0.005	0.02	0.41	0.04	0.005	0.01	0.04	0.26	0.13	0.15	0.09
28.12.2018	0.06	0.005	0.04	1.27	0.13	0.01	0.01	0.04	0.63	0.06	0.11	0.07
29.12.2018	0.09	0.005	0.03	0.88	0.1	0.01	0.01	0.04	0.45	0.08	0.12	0.09
30.12.2018	0.08	0.005	0.02	0.58	0.06	0.01	0.015	0.02	0.33	0.09	0.12	0.12
31.12.2018	0.07	0.005	0.01	0.33	0.02	0.01	0.01	0.02	0.21	0.09	0.11	0.07

Table A.6: Concentrations of trace elements in snow samples in November- December 2019, analysed at CNR-ISP. Unit pg/g.

Sample ID	Na	Mg	Al	K	Ca	Ti	Fe	Cr	Mn	Ni	Cu	Zn	Sr	Cd	Ba	Pb	Li	V	Co	As	Rb	Sb	U
1 BTE 5-15 29.11.2019	1432.63	231.89	14.03	126.32	96.16	3.05	25.41	0.12	1.74	0.19	0.77	4.23	1.49	0.14	1.82	0.21	0.05	0.01	0.03	0.04	0.13	0.01	0.01
3 BTE 5-16 24.11.2019	3977.54	560.58	25.83	300.38	128.90	3.69	49.46	0.11	1.85	0.12	1.02	31.42	3.07	0.01	1.25	0.16	0.09	0.01	0.03	0.04	0.26	0.01	0.01
3 STE 0-5 24.11.2019	762.77	106.24	1.51	37.38	57.34	0.66	1.44	0.00	0.16	0.02	0.11	5.52	0.67	0.00	0.50	0.02	0.01	0.00	0.00	0.00	0.02	0.00	0.00
1 TE 0-12 11.12.2019	1301.35	311.28	23.95	75.02	171.69	4.95	32.49	0.19	3.45	0.22	0.26	1.62	2.51	0.15	1.60	0.63	0.07	0.01	0.04	0.05	0.19	0.02	0.03
1 STE 0-5 29-11-2019	2134.26	267.35	5.46	325.83	96.99	1.64	7.96	0.05	0.84	0.14	2.94	13.24	1.83	0.01	1.10	0.04	0.04	0.00	0.01	0.01	0.25	0.01	0.00
3 TE 0-16 21-11-2019	3131.82	468.63	11.94	135.91	134.14	2.67	33.34	0.08	1.64	0.07	0.10	9.13	2.81	0.00	1.26	0.08	0.07	0.00	0.02	0.02	0.09	0.01	0.00
4 TE 0-7 21-11-2019	4811.52	599.16	4.45	190.94	109.89	1.53	6.27	0.02	0.51	0.06	0.05	7.04	3.46	0.00	0.51	0.06	0.08	0.00	0.00	0.02	0.08	0.01	0.00
2 TE 0-10 21-11-2019	1533.72	194.65	1.69	61.29	45.87	0.44	1.34	0.00	0.15	0.01	\	3.24	1.16	0.00	0.47	0.02	0.03	0.00	0.00	0.01	0.02	0.00	0.00
4 BTE 0-10 11-12-2019	1695.59	308.73	24.41	85.10	140.07	4.30	33.58	0.03	3.13	0.06	0.06	0.81	2.11	0.00	1.06	0.07	0.05	0.01	0.02	0.02	0.19	0.00	0.00
1 BTE 0-100 3-12-2019	1284.89	218.93	10.37	63.12	127.40	2.86	15.74	0.09	0.96	0.12	0.07	8.04	1.44	0.06	0.31	0.09	0.04	0.01	0.01	0.02	0.09	0.01	0.01
2 BTE 5-10 29-11-2019	1638.80	240.06	7.86	111.44	89.84	2.16	17.36	0.05	1.55	0.10	0.38	4.80	1.65	0.05	1.54	0.25	0.05	0.00	0.02	0.03	0.09	0.02	0.01
1 BTE 5-10 26-11-2019	943.49	143.04	4.46	47.21	39.01	0.88	6.98	0.03	0.49	0.05	0.05	1.44	0.80	0.01	0.41	0.09	0.02	0.00	0.00	0.01	0.03	0.01	0.00
3-BTE 5-20 26-11-2019	3101.49	427.02	16.23	177.46	92.30	1.79	17.70	0.03	1.00	0.04	0.23	7.73	2.42	0.00	1.16	0.07	0.06	0.00	0.01	0.02	0.12	0.01	0.01
3 BTE 0-7 10-12-19	3397.16	602.29	35.00	152.64	174.52	5.31	235.45	0.13	4.44	0.20	0.47	17.91	3.15	0.07	0.88	0.19	0.09	0.01	0.08	0.05	0.19	0.01	0.01
6 TE 0-13 21-11-2019	960.09	135.82	3.35	101.03	35.61	0.59	5.37	0.05	0.47	0.09	0.58	4.57	0.84	0.05	0.45	0.06	0.02	0.00	0.01	0.01	0.08	0.01	0.00
2 TE 0-10 24-11-2019	1474.45	180.66	3.64	160.81	57.73	0.66	2.45	0.07	0.31	0.11	1.27	9.51	1.44	0.03	1.75	0.04	0.03	0.00	0.01	0.01	0.11	0.01	0.00
5 TE 0-17 21-11-2019	1895.36	240.60	3.29	76.85	34.11	0.35	3.96	0.07	0.41	0.04	0.01	0.65	1.33	0.02	0.27	0.04	0.03	0.00	0.00	0.01	0.04	0.00	0.00
2-BTE 0-8 3-12-19	993.50	137.56	1.44	44.24	26.34	0.13	1.70	0.00	0.27	0.02	\	0.11	0.77	0.00	0.15	0.01	0.02	0.00	0.00	0.00	0.02	0.00	0.00
2 STE 0-4 26-11-2019	543.15	78.04	4.78	34.43	112.40	1.55	1.81	0.03	0.16	0.06	0.16	14.11	0.65	0.03	0.37	0.03	0.01	0.00	0.00	0.01	0.03	0.01	0.00
3 STE 0-3 11-12-2019	1704.88	689.04	98.60	159.72	393.34	13.99	152.63	0.22	8.29	0.63	0.36	6.20	5.53	0.01	4.42	0.86	0.14	0.01	0.10	0.07	0.51	0.02	0.02
1 BTE 0-12 24-11-2019	1367.94	172.94	2.80	91.12	49.78	0.48	2.80	0.05	0.23	0.09	0.61	4.64	1.03	0.03	0.58	0.02	0.02	0.00	0.00	0.01	0.05	0.00	0.00
TE KOLHAPIVA 0-8 03-12-2019	3591.61	541.40	21.27	155.94	120.32	3.34	37.47	0.07	1.78	0.08	0.09	4.04	3.05	0.01	1.45	0.13	0.08	0.01	0.02	0.03	0.13	0.01	0.01
2 STE 0-5 29-11-2019	1776.89	256.77	14.01	94.59	80.91	2.19	23.77	0.04	1.02	1.71	0.21	3.08	1.96	0.00	1.06	0.04	0.04	0.00	0.02	0.01	0.10	0.00	0.00
2 BTE 4-20 26-11-2019	1688.47	212.47	0.65	68.65	37.34	0.18	0.81	0.00	0.12	0.71	\	1.90	1.25	0.00	0.29	0.02	0.03	0.00	0.00	0.00	0.02	0.00	0.00
3 STE 0-5 26-11-2019	664.06	630.48	1922.11	200.50	320.57	70.80	858.72	1.57	16.47	1.82	0.82	17.61	2.89	0.03	18.59	0.20	0.52	0.13	1.12	0.11	1.06	0.80	0.07
4 STE 0-2 11-12-2019	3573.49	1132.39	143.97	247.87	815.74	25.11	203.21	0.19	17.14	0.94	0.33	1.80	8.39	0.01	4.78	0.42	0.21	0.02	0.13	0.17	0.89	0.01	0.02
1 STE 0-5 26-11-2019	384.07	53.77	2.14	22.76	41.64	0.40	1.27	0.00	0.14	0.95	0.04	4.44	0.55	0.00	0.28	0.02	0.01	0.00	0.00	0.00	0.02	0.00	0.00
3 BTE 3-12 11-12-2019	2980.41	461.89	15.18	125.70	100.17	2.27	27.14	0.05	1.66	1.05	0.27	5.14	2.40	0.00	0.76	0.07	0.06	0.00	0.03	0.04	0.11	0.00	0.00
1TE_0-15	\	\	\	\	\	3.27	\	\	\	\	\	\	\	\	1.97	0.06	0.04	0.00	0.00	0.00	0.00	0.03	0.00
3BTE_0-100	249.80	125.12	31.57	130.84	68.30	37.39	73.30	0.14	1.76	0.11	1.14	6.84	0.32	0.00	11.93	0.62	0.33	0.01	0.04	0.02	0.15	0.05	0.03

Table A.7: Pooled snow samples before and after in November- December 2019 analysed for various POPs at NILU. Unit pg/g..

	24.11.2019				26.11.2019		29/11/19	10.12.2019		11.12.2019
	site 2, ID 2-2	site 3, ID 2-3	site4, ID 1-4	site 1, ID 2-1	site 2, ID 3-2	site 3, ID3-3	Site 1 ID 4-1	site 3, ID 6-3	site 2, ID6-2	site 1, ID 7-1
Dioxins										
2378-TCDD	< 0.206	< 0.126	< 0.130	< 0.211	< 0.106	< 0.180	< 0.175	< 0.260	< 0.126	< 0.284
12378-PeCDD	< 0.186	< 0.136	< 0.140	< 0.161	< 0.111	< 0.247	< 0.185	< 0.254	< 0.133	< 0.261
123478-HxCDD	< 0.140	< 0.164	< 0.167	< 0.213	< 0.137	< 0.140	< 0.196	< 0.283	< 0.164	< 0.171
123678-HxCDD	< 0.140	< 0.164	< 0.168	< 0.177	< 0.138	< 0.140	< 0.229	< 0.238	< 0.164	< 0.168
123789-HxCDD	< 0.140	< 0.164	< 0.167	< 0.186	< 0.137	< 0.140	< 0.225	< 0.247	< 0.164	< 0.168
1234678-HpCDD	< 0.168	< 0.196	0.233	< 0.168	< 0.164	< 0.168		< 0.172	< 0.196	< 0.213
OCDD	< 0.475	< 0.556	1.580	< 0.475	0.465	< 0.475		3.000	< 0.556	< 0.569
SUM PCDD	0.436	0.310	0.320	0.430	0.260	0.470	0.43	0.590	0.310	0.600
Furanes										
2378-TCDF	< 0.129	< 0.089	< 0.103	< 0.095	< 0.075	< 0.139	< 0.097	< 0.111	< 0.089	< 0.214
12378/12348-PeCDF	< 0.125	< 0.115	< 0.117	< 0.141	< 0.096	< 0.178	< 0.109	< 0.133	< 0.115	< 0.156
23478-PeCDF	< 0.126	< 0.103	< 0.105	< 0.143	< 0.086	< 0.180	< 0.11	< 0.134	< 0.103	< 0.157
123478/123479-HxCDF	< 0.075	< 0.080	< 0.081	< 0.103	< 0.067	0.456	< 0.1	< 0.639	< 0.080	< 0.134
123678-HxCDF	< 0.074	< 0.079	< 0.081	< 0.099	< 0.066	0.401	< 0.119	< 0.226	< 0.079	< 0.130
123789-HxCDF	< 0.095	< 0.110	< 0.112	< 0.128	< 0.092	< 0.238	< 0.376	< 0.329	< 0.110	< 0.167
234678-HxCDF	< 0.083	< 0.090	< 0.092	< 0.111	< 0.075	< 0.213	< 0.333	< 0.221	< 0.090	< 0.145
1234678-HpCDF	< 0.096	< 0.112	< 0.114	< 0.108	< 0.127	1.020		< 0.096	< 0.112	< 0.115
1234789-HpCDF	< 0.119	< 0.140	< 0.143	< 0.138	< 0.117	< 0.133		< 0.119	< 0.140	< 0.143
OCDF	< 0.319	< 0.297	< 0.303	< 0.284	< 0.248	< 0.413		< 0.310	< 0.297	< 0.402
SUM PCDF	0.089	0.080	0.080	0.100	0.070	0.220	0.14	0.200	0.082	0.130
SUM PCDD/PCDF	0.525	0.400	0.410	0.530	0.330	0.690	0.56	0.790	0.392	0.730
nonortho - PCB										
33'44'-TeCB (PCB-77)	< 2.030	< 2.380	< 2.430	2.040	< 2.970	< 2.030	1.95	< 2.030	< 2.380	2.580
344'5-TeCB (PCB-81)	0.145	< 0.138	< 0.141	0.188	< 0.268	< 0.118	0.113	< 0.118	< 0.138	< 0.142
33'44'5-PeCB (PCB-126)	< 0.218	< 0.255	< 0.260	< 0.256	< 0.268	< 0.233	0.209	< 0.288	< 0.255	< 0.343
33'44'55'-HxCB (PCB-169)	< 0.171	< 0.469	< 0.126	< 0.212	< 0.329	< 0.201	0.216	< 0.413	< 0.123	< 0.287
SUM TE-PCB	0.027	0.040	0.030	0.030	0.040	0.030	0.03	0.040	0.029	0.040

Table A.8: Concentrations of trace elements in snow samples in November- December 2019. Analysed at NILU. Sample in red indicate the extreme concentrations at site 3 just after the launch 26 Nov, Unit pg/g

sample date	Site, sample ID	Al	V	Cr	Fe	Co	Ni	Cu	Zn	Cd	Pb
21.11.2019	1 BTE 5-15cm	3.54	0.11	<0.09	2.36	0.009	<0.06	<0.05	0.98	<0.006	<0.04
21.11.2019	1 STE 0-5cm	1.82	0.17	<0.09	<0.7	<0.008	<0.06	0.05	2.82	<0.006	<0.04
21.11.2019	1-TE 0-15cm	4.75	0.19	<0.09	4.15	0.009	<0.06	0.07	5.95	<0.006	<0.04
21.11.2019	2 BTE 5-20cm	<1	0.07	<0.09	1.80	0.022	<0.06	<0.05	3.34	<0.006	<0.04
21.11.2019	2 POP 0-5cm	<1	<0.02	<0.09	<0.7	<0.008	<0.06	0.92	8.14	<0.006	<0.04
21.11.2019	2 STE 0-5cm	<1	0.15	<0.09	<0.7	0.010	<0.06	0.07	2.76	<0.006	<0.04
21.11.2019	2-TE 0-10cm	<1	0.14	<0.09	<0.7	<0.008	<0.06	0.05	5.18	<0.006	<0.04
21.11.2019	3 BTE 0-10cm	6.13	0.07	<0.09	9.35	<0.008	<0.06	<0.05	3.41	<0.006	<0.04
21.11.2019	3 POP 0-5cm	<1	0.04	<0.09	<0.7	0.009	<0.06	0.20	8.30	<0.006	<0.04
21.11.2019	3-TE 0-16cm	<1	0.10	<0.09	0.71	0.009	<0.06	<0.05	5.45	<0.006	<0.04
21.11.2019	4 POP 0-5cm	<1	0.03	<0.09	<0.7	<0.008	<0.06	0.57	9.06	0.006	0.04
21.11.2019	4-TE 0-7cm	1.55	0.13	<0.09	0.75	<0.008	<0.06	0.05	8.29	<0.006	<0.04
21.11.2019	5 POP 0-17cm	<1	<0.02	<0.09	<0.7	<0.008	<0.06	0.22	6.50	0.009	<0.04
21.11.2019	5-TE 0-17cm	2.14	0.15	<0.09	1.18	<0.008	<0.06	<0.05	0.73	<0.006	<0.04
21.11.2019	6 POP 0-13cm	<1	<0.02	<0.09	<0.7	<0.008	<0.06	0.84	8.54	<0.006	<0.04
21.11.2019	6-TE 0-13cm	<1	0.19	<0.09	<0.7	<0.008	<0.06	<0.05	1.08	<0.006	<0.04
24.11.2019	1 BTE 0-12cm	1.48	0.13	<0.09	0.74	<0.008	<0.06	0.06	3.55	<0.006	<0.04
24.11.2019	2 POP 0-5cm	<1	<0.02	<0.09	<0.7	<0.008	<0.06	0.18	2.33	<0.006	<0.04
24.11.2019	2 TE 0-10cm	1.51	0.12	<0.09	<0.7	<0.008	<0.06	0.05	2.94	<0.006	<0.04
24.11.2019	3 BTE 5-16cm	1.73	0.09	<0.09	2.66	0.018	<0.06	<0.05	3.87	0.017	<0.04
24.11.2019	3 STE 0-5cm	2.13	0.21	<0.09	1.52	<0.008	<0.06	<0.05	8.16	<0.006	<0.04
26.11.2019	1 BTE 5-16cm	5.01	0.13	<0.09	7.84	0.014	<0.06	0.08	1.50	<0.006	<0.04
26.11.2019	1 STE 0-5cm	1.41	0.17	<0.09	1.27	<0.008	<0.06	0.07	6.26	<0.006	<0.04
26.11.2019	2 BTE 4-20cm	1.42	0.18	<0.09	1.10	<0.008	<0.06	<0.05	2.77	<0.006	<0.04
26.11.2019	2 STE 0-4cm	1.53	0.08	<0.09	1.12	<0.008	<0.06	<0.05	5.65	<0.006	<0.04
26.11.2019	3 BTE 5-20cm	3.80	0.15	<0.09	4.77	0.014	<0.06	<0.05	8.45	<0.006	<0.04
26.11.2019	3 STE 0-5cm	583.7	0.03	<0.09	11.82	0.121	0.35	2.74	14.59	0.042	0.18
03.12.2019	1 POP 0-5cm	<1	<0.02	<0.09	<0.7	<0.008	<0.06	<0.05	6.13	<0.006	<0.04
03.12.2019	1-BTE 0,10cm	1.69	0.22	<0.09	2.48	0.009	<0.06	<0.05	7.85	<0.006	<0.04
03.12.2019	1-BTE 0-10cm	<1	0.07	<0.09	1.75	<0.008	<0.06	<0.05	5.02	<0.006	<0.04
03.12.2019	2-BTE 0-8cm	2.32	0.08	<0.09	2.80	0.009	<0.06	0.05	4.31	<0.006	<0.04
03.12.2019	3 STE 0-5cm	1.42	0.34	<0.09	<0.7	<0.008	<0.06	<0.05	3.43	<0.006	<0.04
03.12.2019	3-TE 0-8cm	1.96	0.20	<0.09	3.36	0.019	<0.06	0.07	1.92	<0.006	<0.04
03.12.2019	3-TE 0-8cm	5.70	0.09	<0.09	8.48	0.024	<0.06	0.06	4.12	<0.006	<0.04
10.12.2019	1 POP 0-5cm	<1	<0.02	<0.09	<0.7	<0.008	<0.06	0.07	6.30	<0.006	<0.04
10.12.2019	3-BTE 0-7cm	11.02	0.24	<0.09	21.11	0.013	<0.06	0.16	3.32	<0.006	0.05
10.12.2019	3-BTE 0-7cm	17.41	0.22	<0.09	30.30	0.079	0.06	0.20	10.14	0.041	0.08
11.12.2019	1 POP 0-5cm	2.54	<0.02	<0.09	0.88	<0.008	<0.06	<0.05	1.54	<0.006	<0.04
11.12.2019	1-TE 0-12cm	1.21	0.07	<0.09	1.57	<0.008	<0.06	<0.05	1.21	<0.006	<0.04
11.12.2019	1-TE 0-12cm	2.85	0.13	<0.09	2.27	<0.008	<0.06	<0.05	<0.6	<0.006	<0.04
11.12.2019	3 POP 0-5cm	12.68	0.04	<0.09	17.10	0.010	<0.06	<0.05	4.68	<0.006	<0.04
11.12.2019	3-B+STE 0-12cm	1.95	0.12	<0.09	2.15	<0.008	<0.06	0.08	3.77	<0.006	<0.04
11.12.2019	3-BTE 3-12cm	<1	0.07	<0.09	1.39	0.010	<0.06	<0.05	4.41	<0.006	<0.04
11.12.2019	3-STE 0-3cm	2.15	0.07	<0.09	1.03	<0.008	<0.06	<0.05	2.02	<0.006	<0.04
11.12.2019	4-BTE 2-10cm	1.40	0.14	<0.09	0.98	<0.008	<0.06	<0.05	1.41	<0.006	<0.04
11.12.2019	4S+BTE 0-10cm	6.59	0.11	<0.09	5.57	<0.008	<0.06	<0.05	1.33	<0.006	<0.04
11.12.2019	4-STE 0-2cm	3.42	0.12	<0.09	<0.7	<0.008	<0.06	<0.05	<0.6	<0.006	<0.04

Table A.9: Al, Fe and Zn flux (mgm^{-2}) in Brøggerbreen glacier snow pack 2018.

Snow depth (cm)	Fe flux	Al flux	Zn flux	Al\Zn	Fe\Zn
95 (surface)	0.05	0.06	0.15	0.39	0.30
90	0.04	0.04	0.11	0.39	0.40
85	0.06	0.06	0.18	0.35	0.33
80	0.09	0.07	0.17	0.40	0.52
75	0.47	0.22	0.26	0.84	1.82
70	0.13	0.08	0.07	1.16	1.73
65	0.05	0.05	0.13	0.40	0.43
60	0.04	0.02	0.18	0.13	0.20
55	0.01	0.02	0.07	0.29	0.09
50	0.01	0.02	0.09	0.25	0.09
45	0.03	0.05	0.23	0.20	0.13
40	0.02	0.04	0.26	0.17	0.07
35	0.28	0.14	0.30	0.47	0.94
30	0.01	0.03	0.12	0.26	0.08
25	0.10	0.09	0.22	0.40	0.43
20	0.36	0.41	0.19	2.21	1.90
15	0.58	0.31	0.09	3.28	6.18
10 (bottom)	0.82	0.45	0.05	8.31	15.30

Table A.10: Al, Fe and Zn flux (mgm^{-2}) in Broggerbreen glacier snow pack 2019.

Snow depth (cm)	Fe flux	Al flux	Zn flux	Al\Zn	Fe\Zn
171(surface)	0.47	0.13	0.06	2.04	7.58
165	0.12	0.06	0.02	2.99	6.54
160	0.58	0.14	0.04	3.34	13.99
155	0.33	0.06	0.05	1.11	6.59
150	0.17	0.07	0.03	2.32	5.85
145	0.27	0.04	0.02	1.76	13.01
140	0.20	0.05	0.05	0.91	3.99
135	0.81	0.11	0.10	1.07	8.07
130	0.23	0.05	0.08	0.63	2.89
125	0.09	0.04	0.02	1.92	4.08
120	0.40	0.08	0.06	1.36	6.39
115	0.13	0.05	0.03	1.42	3.95
110	0.35	0.07	0.06	1.12	5.36
105	0.25	0.13	0.06	2.35	4.39
100	0.33	0.09	0.05	1.75	6.49
95	0.37	0.07	0.07	1.05	5.36
90	0.33	0.13	0.10	1.29	3.28
85	0.26	0.06	0.03	2.34	9.37
80	0.20	0.13	0.03	4.42	6.73
75	0.25	0.07	0.07	1.03	3.55
70	0.29	0.09	0.02	5.55	17.23
65	0.68	0.78	0.33	2.38	2.07
60	0.91	0.37	1.35	0.27	0.67
55	0.33	0.16	0.04	4.50	8.90
50	1.98	1.30	0.08	17.12	26.15
45	0.28	0.05	0.02	2.24	12.24
40	0.13	0.05	0.05	1.02	2.77
35	0.60	0.34	0.06	6.00	10.63
30	5.65	0.23	0.07	3.43	84.23
25	2.97	1.48	0.05	27.27	54.85
20	0.40	0.14	0.05	2.93	8.59
15	0.41	0.24	0.04	6.73	11.43
10	0.49	0.28	0.09	3.23	5.71
5(bottom)	0.72	0.23	0.11	2.03	6.30

Table A.11: Al, Fe and Zn flux (mgm^{-2}) in Brøggerbreen glacier snow pack 2020.

Snow depth (cm)	Fe flux	Al flux	Zn flux	Al\Zn	Fe\Zn
105 (surface)	0.25	0.19	0.37	0.51	0.67
100	0.30	0.12	0.07	1.86	4.54
95	0.10	0.10	0.08	1.15	1.26
90	0.46	0.30	0.09	3.49	5.41
85	0.38	0.18	0.04	4.02	8.48
80	0.11	0.44	0.29	1.51	0.37
75	0.06	0.07	0.13	0.49	0.43
70	0.01	0.02	0.18	0.09	0.06
65	0.03	0.03	0.52	0.05	0.05
60	0.09	0.06	0.17	0.35	0.49
55	0.03	0.03	0.49	0.06	0.06
50	0.03	0.03	0.27	0.10	0.11
45	0.05	0.05	0.11	0.46	0.41
40	0.09	0.07	0.15	0.43	0.59
35	0.41	0.35	0.04	8.87	10.54
30	0.12	0.09	0.01	14.79	20.60
25	0.04	0.03	0.00	7.13	10.29
20	0.22	0.11	0.01	20.31	38.81
15	0.24	0.12	0.02	5.85	11.11
10	0.17	0.09	0.04	2.01	4.07
5	0.12	0.07	0.04	2.02	3.35
0 (bottom)	0.05	0.02	0.05	0.54	1.06

Table A.12: Al, Fe and Zn flux (mgm^{-2}) in Midtre Lovenbreen glacier snow pack 2018

Snow depth (cm)	Fe flux	Al flux	Zn flux	Al\Zn	Fe\Zn
167 (surface)	0.09	0.10	0.34	0.30	0.26
160	0.06	0.06	0.06	1.01	1.06
155	0.07	0.05	0.07	0.79	1.04
150	0.12	0.09	0.09	1.06	1.33
144	0.96	0.39	0.13	2.96	7.28
139	0.25	0.16	0.11	1.50	2.36
134	0.03	0.02	0.04	0.49	0.70
129	0.05	0.04	0.08	0.50	0.64
124	0.01	0.02	0.12	0.16	0.09
118	0.01	0.01	0.04	0.32	0.14
113	0.03	0.03	0.12	0.23	0.27
108	0.09	0.06	0.18	0.31	0.49
103	0.70	0.29	0.06	4.93	12.11
98	0.04	0.02	0.08	0.28	0.45
92	0.02	0.03	0.04	0.83	0.40
87	0.19	0.13	0.08	1.64	2.38
82	0.28	0.18	0.07	2.39	3.78
77	0.16	0.13	0.12	1.16	1.42
72	0.10	0.08	0.27	0.28	0.36
66	0.12	0.07	0.24	0.30	0.50
61	0.04	0.05	0.08	0.70	0.55
56	0.04	0.11	0.15	0.69	0.25
51	0.07	0.05	0.10	0.51	0.70
46	0.14	0.09	0.06	1.63	2.52
40	0.07	0.05	0.08	0.56	0.78
35	0.13	0.17	0.07	2.64	2.01
30	0.30	0.33	0.16	2.04	1.87
25	2.69	1.38	0.12	11.66	22.71
20	3.38	1.75	0.12	14.53	27.96
14	0.64	0.35	0.11	3.10	5.64
9	0.28	0.17	0.10	1.80	2.96
4 (bottom)	0.02	0.02	0.09	0.24	0.23

Table A.13: Al, Fe and Zn flux (mgm^{-2}) in Midtre Lovenbreen glacier snow pack 2019

Snow depth (cm)	Fe flux	Al flux	Zn flux	Al\Zn	Fe\Zn
195(surface)	0.23	0.09	0.05	1.70	4.53
190	2.20	0.11	0.04	2.71	52.94
185	0.14	0.06	0.03	1.79	3.99
180	0.07	0.03	0.01	2.64	7.14
175	0.76	0.31	0.05	6.04	14.86
170	0.22	0.07	0.02	4.09	12.48
165	0.17	0.10	0.05	2.01	3.48
160	0.50	0.09	0.06	1.61	9.01
155	0.22	0.09	0.08	1.19	2.78
150	0.17	0.05	0.04	1.24	4.36
145	0.21	0.07	0.06	1.19	3.55
140	0.21	0.13	0.09	1.49	2.42
135	0.16	0.09	0.15	0.56	1.05
130	0.37	0.28	0.09	3.21	4.20
125	0.23	0.08	0.04	2.13	6.44
120	2.74	0.10	0.09	1.09	29.55
115	0.21	0.11	0.06	1.74	3.38
110	0.25	0.11	0.08	1.38	3.28
105	0.15	0.08	0.01	5.86	10.09
100	0.56	0.11	0.11	1.02	5.20
95	0.52	0.12	0.13	0.94	4.14
90	0.34	0.10	0.05	2.01	6.77
85	0.15	0.05	0.02	2.17	6.95
80	0.17	0.06	0.03	1.61	4.78
75	0.20	0.08	0.03	2.49	5.81
70	0.46	0.11	0.16	0.71	2.99
65	0.44	0.15	0.08	1.83	5.41
60	0.67	0.75	0.20	3.76	3.36
55	0.54	0.42	0.15	2.80	3.60
50	0.65	0.40	0.05	8.44	13.63
45	0.62	0.23	0.14	1.56	4.33
40	0.74	0.37	0.14	2.63	5.19
35	1.74	0.11	0.07	1.64	26.09
30	1.46	0.25	0.13	1.99	11.41
25	0.38	0.24	0.09	2.61	4.23
20	0.34	0.17	0.05	3.70	7.43
15	0.47	0.87	0.31	2.80	1.51
10	0.31	0.09	0.18	0.47	1.72
5(bottom)	0.56	0.13	0.18	0.74	3.19

Table A.14 Al, Fe and Zn flux (mgm^{-2}) in Midtre Lovenbreen glacier snow pack 2020

Snow depth (cm)	Fe flux	Al flux	Zn flux	Al\Zn	Fe\Zn
123(surface)	0.07	0.07	0.02	4.61	4.93
118	0.29	0.25	0.03	9.63	11.28
113	0.02	0.02	0.03	0.92	0.85
108	0.41	0.26	0.02	16.74	26.03
103	0.45	0.33	0.06	5.58	7.62
98	0.13	0.18	0.04	4.33	3.13
93	0.19	0.15	1.02	0.15	0.19
88	0.02	0.02	0.13	0.15	0.12
83	NA	NA	NA	NA	NA
78	0.03	0.04	0.21	0.21	0.15
73	0.04	0.05	0.08	0.62	0.47
68	0.03	0.04	0.16	0.27	0.21
63	0.04	0.04	0.13	0.30	0.33
58	0.04	0.04	0.05	0.83	0.78
53	0.04	0.06	0.04	1.61	0.97
48	0.33	0.28	0.03	9.60	11.56
43	0.34	0.33	0.02	15.39	16.27
38	1.06	0.80	0.08	9.70	12.90
33	0.11	0.09	0.03	2.77	3.62
28	0.04	0.03	0.03	1.30	1.56
23	0.02	0.01	0.02	0.57	0.66
18	0.01	0.01	0.02	0.35	0.58
13	0.25	0.11	0.02	5.25	11.55
8	0.28	0.18	0.02	9.54	15.04
3(bottom)	0.12	0.09	0.02	5.59	7.47

Table A.15: Snow samples before and after launch in Nov - Dec 2019 analysed for trace elements. The sample at site 3 just after the launch is highlighted due its extreme concentrations. Unit pg/g.

sample date	Site, sample	Al	V	Cr	Fe	Co	Ni	Cu	Zn	Cd	Pb
21.11.2019	1 BTE 5-15cm	3.54	0.11	<0.09	2.36	0.009	<0.06	<0.05	0.98	<0.006	<0.04
21.11.2019	1 STE 0-5cm	1.82	0.17	<0.09	<0.7	<0.008	<0.06	0.05	2.82	<0.006	<0.04
21.11.2019	1-TE 0-15cm	4.75	0.19	<0.09	4.15	0.009	<0.06	0.07	5.95	<0.006	<0.04
21.11.2019	2 BTE 5-20cm	<1	0.07	<0.09	1.80	0.022	<0.06	<0.05	3.34	<0.006	<0.04
21.11.2019	2 POP 0-5cm	<1	<0.02	<0.09	<0.7	<0.008	<0.06	0.92	8.14	<0.006	<0.04
21.11.2019	2 STE 0-5cm	<1	0.15	<0.09	<0.7	0.010	<0.06	0.07	2.76	<0.006	<0.04
21.11.2019	2-TE 0-10cm	<1	0.14	<0.09	<0.7	<0.008	<0.06	0.05	5.18	<0.006	<0.04
21.11.2019	3 BTE 0-10cm	6.13	0.07	<0.09	9.35	<0.008	<0.06	<0.05	3.41	<0.006	<0.04
21.11.2019	3 POP 0-5cm	<1	0.04	<0.09	<0.7	0.009	<0.06	0.20	8.30	<0.006	<0.04
21.11.2019	3-TE 0-16cm	<1	0.10	<0.09	0.71	0.009	<0.06	<0.05	5.45	<0.006	<0.04
21.11.2019	4 POP 0-5cm	<1	0.03	<0.09	<0.7	<0.008	<0.06	0.57	9.06	0.006	0.04
21.11.2019	4-TE 0-7cm	1.55	0.13	<0.09	0.75	<0.008	<0.06	0.05	8.29	<0.006	<0.04
21.11.2019	5 POP 0-17cm	<1	<0.02	<0.09	<0.7	<0.008	<0.06	0.22	6.50	0.009	<0.04
21.11.2019	5-TE 0-17cm	2.14	0.15	<0.09	1.18	<0.008	<0.06	<0.05	0.73	<0.006	<0.04
21.11.2019	6 POP 0-13cm	<1	<0.02	<0.09	<0.7	<0.008	<0.06	0.84	8.54	<0.006	<0.04
21.11.2019	6-TE 0-13cm	<1	0.19	<0.09	<0.7	<0.008	<0.06	<0.05	1.08	<0.006	<0.04
24.11.2019	1 BTE 0-12cm	1.48	0.13	<0.09	0.74	<0.008	<0.06	0.06	3.55	<0.006	<0.04
24.11.2019	2 POP 0-5cm	<1	<0.02	<0.09	<0.7	<0.008	<0.06	0.18	2.33	<0.006	<0.04
24.11.2019	2 TE 0-10cm	1.51	0.12	<0.09	<0.7	<0.008	<0.06	0.05	2.94	<0.006	<0.04
24.11.2019	3 BTE 5-16cm	1.73	0.09	<0.09	2.66	0.018	<0.06	<0.05	3.87	0.017	<0.04
24.11.2019	3 STE 0-5cm	2.13	0.21	<0.09	1.52	<0.008	<0.06	<0.05	8.16	<0.006	<0.04
26.11.2019	1 BTE 5-16cm	5.01	0.13	<0.09	7.84	0.014	<0.06	0.08	1.50	<0.006	<0.04
26.11.2019	1 STE 0-5cm	1.41	0.17	<0.09	1.27	<0.008	<0.06	0.07	6.26	<0.006	<0.04
26.11.2019	2 BTE 4-20cm	1.42	0.18	<0.09	1.10	<0.008	<0.06	<0.05	2.77	<0.006	<0.04
26.11.2019	2 STE 0-4cm	1.53	0.08	<0.09	1.12	<0.008	<0.06	<0.05	5.65	<0.006	<0.04
26.11.2019	3 BTE 5-20cm	3.80	0.15	<0.09	4.77	0.014	<0.06	<0.05	8.45	<0.006	<0.04
26.11.2019	3 STE 0-5cm	583.7	0.03	<0.09	11.82	0.121	0.35	2.74	14.59	0.042	0.18
03.12.2019	1 POP 0-5cm	<1	<0.02	<0.09	<0.7	<0.008	<0.06	<0.05	6.13	<0.006	<0.04
03.12.2019	1-BTE 0,10cm	1.69	0.22	<0.09	2.48	0.009	<0.06	<0.05	7.85	<0.006	<0.04
03.12.2019	1-BTE 0-10cm	<1	0.07	<0.09	1.75	<0.008	<0.06	<0.05	5.02	<0.006	<0.04
03.12.2019	2-BTE 0-8cm	2.32	0.08	<0.09	2.80	0.009	<0.06	0.05	4.31	<0.006	<0.04
03.12.2019	3 STE 0-5cm	1.42	0.34	<0.09	<0.7	<0.008	<0.06	<0.05	3.43	<0.006	<0.04
03.12.2019	3-TE 0-8cm	1.96	0.20	<0.09	3.36	0.019	<0.06	0.07	1.92	<0.006	<0.04
03.12.2019	3-TE 0-8cm	5.70	0.09	<0.09	8.48	0.024	<0.06	0.06	4.12	<0.006	<0.04
10.12.2019	1 POP 0-5cm	<1	<0.02	<0.09	<0.7	<0.008	<0.06	0.07	6.30	<0.006	<0.04
10.12.2019	3-BTE 0-7cm	11.02	0.24	<0.09	21.11	0.013	<0.06	0.16	3.32	<0.006	0.05
10.12.2019	3-BTE 0-7cm	17.41	0.22	<0.09	30.30	0.079	0.06	0.20	10.14	0.041	0.08
11.12.2019	1 POP 0-5cm	2.54	<0.02	<0.09	0.88	<0.008	<0.06	<0.05	1.54	<0.006	<0.04
11.12.2019	1-TE 0-12cm	1.21	0.07	<0.09	1.57	<0.008	<0.06	<0.05	1.21	<0.006	<0.04
11.12.2019	1-TE 0-12cm	2.85	0.13	<0.09	2.27	<0.008	<0.06	<0.05	<0.6	<0.006	<0.04
11.12.2019	3 POP 0-5cm	12.68	0.04	<0.09	17.10	0.010	<0.06	<0.05	4.68	<0.006	<0.04
11.12.2019	3-B+STE 0-12cm	1.95	0.12	<0.09	2.15	<0.008	<0.06	0.08	3.77	<0.006	<0.04
11.12.2019	3-BTE 3-12cm	<1	0.07	<0.09	1.39	0.010	<0.06	<0.05	4.41	<0.006	<0.04
11.12.2019	3-STE 0-3cm	2.15	0.07	<0.09	1.03	<0.008	<0.06	<0.05	2.02	<0.006	<0.04
11.12.2019	4-BTE 2-10cm	1.40	0.14	<0.09	0.98	<0.008	<0.06	<0.05	1.41	<0.006	<0.04
11.12.2019	4S+BTE 0-10cm	6.59	0.11	<0.09	5.57	<0.008	<0.06	<0.05	1.33	<0.006	<0.04
11.12.2019	4-STE 0-2cm	3.42	0.12	<0.09	<0.7	<0.008	<0.06	<0.05	<0.6	<0.006	<0.04

Table A.16: Results from overbank sediments collected in impact areas and reference point in Brøggerdalen.

component	unit	**P1** *78° 54.59'N, 11° 49.41'E*	**P2** *78° 54.59'N, 11° 49.41'E*	**P3** *78° 54.61'N, 11° 49.40'E*	**P4** *78° 55.33'N, 11° 49.43'E*
Aromater >C8-C10	mg/kg TS	< 4,0	< 4,0	< 4,0	< 4,0
Aromater >C10-C16	mg/kg TS	< 0,90	< 0,90	< 0,90	< 0,90
Aromater >C16-C35	mg/kg TS	< 0,50	< 0,50	< 0,50	< 0,50
Methylchrysener/ benzo(a)anthracener	mg/kg TS	< 0,50	< 0,50	< 0,50	< 0,50
Methylpyrene/fluoranthense	mg/kg TS	< 0,50	< 0,50	< 0,50	< 0,50
Tørrstoff	%	80,3	82,4	91,8	84,8
Arsen (As)	mg/kg TS	2,0	2,2	2,1	3,6
Bly (Pb)	mg/kg TS	8,2	8,8	6,8	8,5
Kadmium (Cd)	mg/kg TS	0,63	16	< 0,20	< 0,20
Kobber (Cu)	mg/kg TS	11	14	9,4	13
Krom (Cr)	mg/kg TS	12	23	7,1	10
Kvikksølv (Hg)	mg/kg TS	< 0,010	< 0,010	< 0,010	< 0,010
Nikkel (Ni)	mg/kg TS	13	15	10	13
Sink (Zn)	mg/kg TS	36	56	28	37
Alifater C5-C6	mg/kg TS	< 7,0	< 7,0	< 7,0	< 7,0
Alifater >C6-C8	mg/kg TS	< 7,0	< 7,0	< 7,0	< 7,0
Alifater >C8-C10	mg/kg TS	< 3,0	< 3,0	< 3,0	< 3,0
Alifater >C10-C12	mg/kg TS	< 5,0	< 5,0	< 5,0	< 5,0
Alifater >C12-C16	mg/kg TS	< 5,0	< 5,0	< 5,0	< 5,0
Alifater >C16-C35	mg/kg TS	< 10	< 10	< 10	< 10
Alifater >C12-C35		**nd**	**nd**	**nd**	**nd**
Alifater C5-C35		**nd**	**nd**	**nd**	**nd**
Benzen	mg/kg TS	< 0,0035	< 0,0035	< 0,0035	< 0,0035
Toluen	mg/kg TS	< 0,10	< 0,10	< 0,10	< 0,10
Etylbenzen	mg/kg TS	< 0,10	< 0,10	< 0,10	< 0,10
m/p/o-Xylen	mg/kg TS	< 0,10	< 0,10	< 0,10	< 0,10
Benzo[a]antracen	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Krysen/Trifenylen	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Benzo(b,k)fluoranten	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Benzo[a]pyren	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Indeno[1,2,3-cd]pyren	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Dibenzo[a,h]antracen	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Naftalen	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Acenaftylen	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Acenaften	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Fluoren	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Fenantren	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Antracen	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Fluoranten	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Pyren	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
Benzo[ghi]perylen	mg/kg TS	< 0,030	< 0,030	< 0,030	< 0,030
PCB 28	mg/kg TS	< 0,0020	< 0,0020	< 0,0020	< 0,0020
PCB 52	mg/kg TS	< 0,0020	< 0,0020	< 0,0020	< 0,0020
PCB 101	mg/kg TS	< 0,0020	< 0,0020	< 0,0020	< 0,0020
PCB 118	mg/kg TS	< 0,0020	< 0,0020	< 0,0020	< 0,0020
PCB 138	mg/kg TS	< 0,0020	0,0024	< 0,0020	< 0,0020
PCB 153	mg/kg TS	< 0,0020	< 0,0020	< 0,0020	< 0,0020
PCB 180	mg/kg TS	< 0,0020	< 0,0020	< 0,0020	< 0,0020
Sum 7 PCB	mg/kg TS		**< 0,0070**		

Appendix B

Snow sampling protocol 2019

Snow sampling survey 2019

By J.-C. Gallet and Christina A. Pedersen, NPI

This document was written prior to the rocket launches in 2019 to give an overview on how the snow sampling should be done. Some minor modification are done for this report

What

NPI and CNR monitor every year the content in glacier and ground snow regarding trace element originated from the Earth' crust (Al, Fe, Co…). Some of these are the same as will be emitted by the rocket. In addition to these, we would also measure the amount of black carbon (BC) is snow, as any combustion produces BC.

How

Univ of Venice uses the IMS102 table for trace elements (TE). This is basically a standard set of reference samples used to calibrate the instrument (known values), and then measure the same elements in the snow, 29 different elements in total. See below for details on the method and elements analyzed. NILU can also measure for trace elements (TE). See below for details on this method.

Measurements for BC will be done by University of Perugia, Italy, using standard Sunset instrument and a common protocol adopted in Europe (EUSAAR_2). For the BC analysis, the snow is sampled, melted, filter on quartz microfiber and then thermo-optical method is used to determine the elemental carbon (EC, used as a proxy for BC) and the organic carbon content (OC). Both EC and OC are summed up to determine the total carbon content (TC).

Sample types

We will focus first on a single surface snow sample, the top 5 cm of the snow for the POP and a bulk sample for TE and BC, avoiding the last 3 cm at the bottom of the snow pack. This is likely to be the best strategy according to the field conditions (update few days before launch). If a new fresh snow layer comes, distinguishable and sample can be taken properly, a surface layer will be added to the bulk above, but not for the POP. Only the 5 top cm will remain sampled for POP.
If two samples (surface and bulk for TE and BC), the sum of both gives the total load. We can hence estimate what is the load of the rocket launch on snow compared to the annual load.

Metadata

In addition some metadata on snow and climate conditions should be collected. For ex. modelers require parameters on mass of impurity per sq. meter of snow surface, which can be converted from what we measure (mass of impurity per mass of snow) by knowing the snow density. Basic climate conditions are also important to estimate potential artifacts or outliers due to wind or melting for example.

We will have access to the data collected by the team working on the rocket, they launch a first balloon at 4:30 local every day during the launching window, and about 5 per days if the day may be a launching one (time window for launch is 8:30-13:00 local). Balloon goes up to 20-23 km and measure the wind.

Site selection

Previously worked done in connection to the 2018 rocket launch considered 6 sampling site. We want to keep some of these sites for consistency, but we have been changing the exact placement of them, in order to choose a flat area where the deposited aerosols and snow will be the less disturbed by topography and/or close ground still not snow covered. A reconnaissance has been made and site selected according to topography and snow conditions (amount, driving conditions).

One special site has been chosen just behind the launching site (flyplass kysten, nr 3), in order to collect possibly the most loaded sample and facilitate the lab work for identification of the pollutant. Thus, the lab can target these compounds and adapt the calibration procedure consequently.
The six sites are 1. Gruvebadet, 2. Kollahaugen, 3. Flyplass kysten, 4. Knudsenheia, 5. Vestre Loven Elva, 6. Ny-Ålesund Brua.

The 2 closest sites to the airport (1, 2) and Gruvebadet (3) where a lot of monitoring activities and undertaken are chosen as the intensive sites where sampling will be performed more often. Zeppelin was included last time, but it is only suitable for sampling if we have calm and quit wind conditions. We have been suggesting an alternative site instead of Zeppelin (6). The way to Corbel is pretty rocky, and far in term of distance to the launch compared to the other sites. Considering also the most prevailing wind directions, we suggest site nr 5 alternatively to Corbel.

Duplicate samples
All samples will be collected using the same vials, procedure, and handling process, see below. Blank can be taken by simply adding ultra pure water in an empty vials.

For Black Carbon (BC), one large bag is sufficient, and no duplicate samples are needed, as the volume of snow taken is large and represent a large surface area/volume of snow, which again represents the natural variability.

POP will be collected in large stainless steel pot and glass jar to avoid any contamination by plastic jar and also collect a large volume. We need at least 10 L of snow (2 L melted water).

All samples should be taken at the same spot, at the same time.

Sample type
First we take one single bulk sample and follow its changes. If a new snow layer comes, and we can easily distinguish it from the previous one, we will had a surface sample for TC and BC only. POP will remain at the top 5 cm of the snow as this is where we do expect to have the deposited material. We may have two types of surface samples and two types on bulk samples, one for trace elements (TE) and one for BC, hence 4 different samples (STE, SBC, BTE, BBC) at each location each time. POP and the site location concern the top 5 cm at the site for each sampling.

Bulk sample: this represent the entire snow pack (minus 3 bottom cm, i.e. contamination) and taken for TE and BC. If an extra fresh snow layer comes, we will had a surface sample, and will continue on taking the bulk sample above. However, the bulk will then not consist anymore of the entire thickness, but the total thickness minus the new fresh layer. We keep consistency on sampling the same thickness over time for the bulk for each site. Combining surface and bulk allows us to estimate the full load in the snow pack, so we can compare the potential impact (of the surface) on the total load.

Surface samples: sample the top layer of the snow, whatever its thickness is (1, 2, 5, or 18 cm). This represent the snow-atmospheric layer and this is where the contaminant will be deposited (dry or wet).

If the snow is only made of one single thin layer, then we just take one sample – the bulk sample.

We should avoid to sample too close to the ground, to avoid contamination (organic matter, soil, chemical produced by bacteria/plants) in the sample.

Snow sampling
Suggestions for sample days are given in the excel file.
All samples should be done in one day in order to sample the same snow.
We should avoid sampling at very windy days since the snow will be blowing and it is difficult to separate the layers, or know what you are sampling.

Timing
Sampling before launch:
Samples should be collected at least once before the launch window starts. Sample all 6 sites.

Sampling in launch window:
Since the launch window is 16 days, we need to re-sample for background values if the rocket launch is not taking place within the first 4-7 days. When there is no precipitation we re-sample every 4-7 days. If there are precipitation we try to sample the day after to estimate what might have naturally been deposited on the snow. This is repeated until the rocket is launched.
There will be two rocket launches, but most probably they will happen with only minutes apart.

Sampling after launch:
The same afternoon as the launch, sample the three intensive sites for immediate deposition.
The day after the launch (+ 24 hrs from launching), sample all six sites for potential delay of deposition (gravity, turbulence, peak time deposition was about 20 h after launch last year).
One week after launch, repeat three closest sites for a final deposition overview.

Summary table, and number of samples:

Timing (tentative)	Sites	Surface samples (if fresh snow)	Bulk samples	Total samples
Friday 22.11	ALL		6 BTE 6 BBC	24
Monday 25.11	3	3 STE 3 SBC	3 BTE 3 BBC	12
Waiting window (to be repeated X days)	3	3 STE 3 SBC	3 BTE 3 BBC	12 (Times X repeat day)
Launch Day	3	3 STE 3 SBC	3 BTE 3 BBC	12
Launch Day +1	ALL	6 STE 6 SBC	6 BTE 6 BBC	24
Launch day + 1 week	3	3 STE 3 SBC	3 BTE 3 BBC	12
		Estimated total samples: 96 plus 12 every sample day in waiting window		

If the weather is really bad, especially on the wind side, you just wait for a good window, as close as possible to the launch or desired timing. It is not necessary to go out by strong wind, the snow is blowing and what you are sampling in the scoop as well. Bad weather for snow sampling starts at about 7-8 m.s-1 wind.

This closes the experiment for the winter. In spring, snow samples will be collected at the glaciers (Midtre Lovenbreen, Edithbreen and Austre Brøggerbreen) for total loads, as well for the six sites. These will be done by scientists from NPI and CNR as part of their annual monitoring.

The following description for snow sampling (snow protocol) is based on the published protocol from the C2S3 project, funded by SSF in 2016 (Gallet et al, 2018, https://data.npolar.no/publication/a4bf6a90-becf-488e-ad6b-2633a0f17504)

Snow sampling protocol

Preparing the snow pit
Not too close to any building (wind drift), 100 meters from anything laying around, avoid area where the ground is exposed.

Metadata

- Take a panoramic photo of the site (especially important to determine possible local influences, such as proximity of bare ground, for example).
- Date and local time
- Complete the excel meta dataform.
- Estimated distance to topographic obstacles, bare ground, nunataks, open water, or anything that you judge could affect the snow pack conditions in the comment field.

Snow sampling snow for BC, POP and TE
BC is usually present in very small amounts in polar snow, and the risk of contaminating samples is high if appropriate precautions are not taken. Possible sources of contamination are scooter exhaust, cigarette smoke and clothes that can catch particles. Therefore, when traveling by snowmobiles, or when sampling in areas where people have been driving snow scooters, move away from the traffic path (often the central line on a glacier), and park and turn off your snowmobile at least 50 m downwind of the sampling site (i.e,. walk at least 50 m upwind).

Do not sample while wearing your snowmobile suit and gloves. Cover your clothes with extra-large non-particulating coverall suit and disposable plastic gloves. Pull the hood of the coverall suit on your head and over your hat. Sample with the coverall for all samples type.

TE sampling
Fill two 50 mL vial full (one for Italy, one for NILU, for each sampling depth). You can densify the snow a bit by pushing more snow into it. Make sure the vials for chemistry are properly closed. Label them and put them into a plastic bag once back, with extra label and one bag for Italy, one for NILU. (Label: Site – (S or B)TE- XX-XX cm, Date).
You can also take an extra TE bulk sample (STE + BBE depth sampling) in the 500 mL plastic bottles, as a back-up, if you have enough vials.

BC sampling
Fill in the bag, you can densify it by tapping it up and down on the ground. One large bag (4-5 l of snow, 2-3 l melted water) is sufficient. Close the bag and put another plastic bag around to avoid leakage when melting (snow is very abrasive). Label the bag (Site - BBC XX-XX cm, Date)

POP sampling

POP should be sampled in the way than BC, with protection and coverall and the stainless stell container should be field (or the glass jar). We need a minimum of 2 L of melted water, and the snow should be melted slowly at room temperature and stored in the fridge at 4 degrees. ¤ jars should be taken if you have enough, or 3 would work if you densify a bit the snow. Once melted, fill back the water in one single jar, or in the plastic bottles (4 of them, they are 500 mL), and label them (Site- POP-0-5 cm, Date)

The samples vials need to be rinsed and prepare beforehand using a peer-reviewed protocol (ultra pure water, Nitric acid). 150 vials are cleaned.
Pre-baked filter for BC are also needed and 100 filters are ready.
All the sampling equipment (suits, bags, scraps etc.) must be kept sealed in plastic bags until they are ready to be used, in order to avoid contamination.
Glass jar that are emptied for POP need to be rinsed with MQ water, and then a little bit of methanol, and dried off during one night (keep them open in the lab, methanol evaporates quickly).

Surface samples:
It is crucial to keep a large area of clean and untouched snow in order to collect the amount of snow needed as close as the other samples taken further down. **Protect your sampling area!**

Bulk samples
Make a new clean straight face by removing the outer 10-20 cm from the sampling face of the snow pit using a clean plastic tool. Before sampling, carefully 'rinse off' all the tools in the snow to be used by pushing them in and out of a clean part of the snow pit wall several times.

1 person is sampling, the other is labelling. Write the label directly on it, let it dry a bit otherwise the ink disappear. Make sure the vials for chemistry are properly closed.

Storing
After sampling, the TE samples need to be kept frozen until analyses. The BC samples will be processed on site (melting, filtering). If not, BC samples should be stored frozen in a freezer. Only POP samples can be melted and sent as water. The rest should be kept frozen.

Specification for TE analysis CNR

<u>Elements list (IMS-102 certified standards for ICP-MS)</u>
Li; Be; Na; Mg; Al; K; Ca; V; Cr; Mn; Fe; Co; Ni; Cu; Zn; As; Se; Rb; Sr; Ag; Cd; Cs; Ba; Tl; Pb; Bi; U
Additional few elements can be added/measured if necessary

<u>Results time line</u>
The results will be release 60 days after receiving the samples. Delay could be caused in case of instrument problems\failure we can’t predict.

<u>Instrument</u>
single quadrupole (SQ) ICP-MS – *Thermo Scientific iCAP RQ ICP-MS*

The LOD (Limit of Detection) depends on the element and the preparation of material as well by the sample handling. It is difficult to estimate procedural blank before measuring it but in general for the Svalbard snow there should be no problem for the concentration range expected.

<u>Sampling material preparation</u>

The vials should be acid cleaned before sampling. Fill the vial with 2% solution of HNO3 Suprapur (SUP) grade or higher. Leave the acid solution in the vials for at least 5 days and rise with Ultra-pure water for 3 times, than dry under a clean laminar flow bench if possible. Avoid the contact with any metal tools

Determination of the contamination on the glacier:
By using the ratio of trace element normally found in natural source (crustal element), it is possible to determine if a source other than natural has loaded the sample. This is how it has been seen that deposition of Al and Fe happened on BRG and Mid. Loven (ratio higher and out of any natural source). In the 80s, this is how they determined the level of contamination of lead when it was still in use in gasoline.

Trace elements analyses in snow samples analyses by NILU

Sample preparation
All samples are added supra pure HNO_3 to 1% (v/v) before analysis.

Instrumental analysis
The metal concentrations will be determined by the use of inductively plasma mass spectrometry (ICP-MS) type Agilent 7700x. All samples, standards, certified reference material (CRM) and blank samples are added indium as internal standard. The calibration curve will be verified by analyzing control samples before real samples are analyzed. A CRM from NIST (1640a Trace element in natural water) are analyzed in every run.

LODs varies from element to element but are manly in ppt level. Uncertainty < 20%.

Trace elements
For the snow samples we use an extended method during analysis and from the obtained raw data we choose the most relevant and interesting results to report.

Appendix C

Method description for trace analysis at CNR-ISP

Object: **Analysis of trace elements in Ny-Ålesund snow samples - Analytical report**

Commitment: Andøya Space Center
Authors: Dr. Andrea Spolaor and Dr. Clara Turetta

Analytical techniques

The determination of trace elements was carried out with inductively coupled plasma-mass spectrometry (ICP-MS) using an iCAP RQ (Thermo Scientific) instrument. The ICP-MS was equipped with an ASX-560 autosampler (Teledyne Cetac Technologies), PolyPro PFE nebulizer, PFE cyclonic spray chamber thermostated at 2.7°C, sapphire injector, quartz torch and Ni cones. The acquisition was performed at 1550 W of plasma RF power in Kinetic Energy Discrimination (KED) – high matrix mode, using He as the collision gas (4.3 mL min^{-1}). Instrument parameters were optimized for best sensitivity in the whole mass range, and minimum oxides (<1%) and double charges (<3%). A total of 27 elements were measured in triplicate acquisitions. Quantification was obtained by external calibration with multi-elemental standards prepared in Milli-Q water (18 MΩ cm^{-1} at 25°C) with 2% v/v ultrapure grade HNO_3 (Romil) from a multi-elemental solutions ICUS 1616 from UltraScientific. Rhodium was continuously spiked to the sample flow through a y-junction and acquired as the internal standard to compensate for possible matrix effects and instrumental drifts during the analytical run. The internal standard spike solution was also prepared in Milli-Q water with ultrapure grade HNO_3 2% v/v from a certified level monoelemental solution (UltraScientific). Analytical quality control was performed by memory test blank (repeated analysis of ultrapure grade HNO_3 2% v/v blank solution) after each sample and calibration verification (repeated analysis of reference materials) every 11 samples. The elements measured are: Na, Mg, Al, K, Ca, Ti, Fe, Cr, Mn, Ni, Cu, Zn, Sr, Cd, Ba, Pb, Li, V, Co, As, Rb, Mo, Ag, Sb, Cs, Tl, U.

Samples treatment and standard

Samples were melted at room temperature under a laminar flow bench (class 100). After melting, the samples were acidified with Ultra-Pure Nitric acid (UPA HNO_3, Sigma Aldrich) for a final acid concentration of 2%. The samples were keep melted for the 24 hours previous the analysis. Calibration standard were prepared by subsequent dilution of the ICUS 1616 Inorganic custom standard (Ultra Scientific, US) in 2% HNO_3 ultra-pure water solution (ELGA water purifying water system). All calibration curve shows a liner fitting >99%.

Recovery and LOD

All the describe results are reported in the excel file associate to the report. Elements in red in the results section should not be considered for further evaluation. The quality control has been assured by testing the instrument using as reference the TMRAIN-04 reference material. The internal standard recovery was always >85% throughout the entire sequence of analysis for almost all elements measured. Three elements must not be considered in the data evaluation, Mo, Ag and Cs since they do not pass the recovery test. Titanium (Ti) do not pass the recovery test as well, but the results obtained from the analysis well agree with the other trace elements measurements. Could be possible that Ti was contaminated in the reference material and not in the samples measured as also suggest by the low detection limits obtained. Consider using Titanium in the data evaluation only if necessary. Limit of detection for each element was calculate from the blank values. The LOD is calculate as three time the standard deviation obtained from 5 blank measurements. All elements have concertation above LOD except Thallium (Tl), its concentration are always below the LOD and should not be considered.

Recommendations:

- Do not use\consider Mo, Ag and Cs since they fail the recovery test
- Do not use\consider Thallium (Tl) since its concentration are always below the LOD
- Use with caution the results obtained for Ti

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NILU – Norwegian Institute for Air Research
P.O. Box 100, NO-2027 KJELLER, Norway

E-mail: nilu@nilu.no
http://www.nilu.no

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