INFLUENCE OF LOCAL AND REGIONAL AIR POLLUTION ON ATMOSPHERIC MEASUREMENTS IN NY-ÅLESUND

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ABSTRACT

The Zeppelin observatory is a research station near the village Ny-Ålesund in Svalbard. The facility delivers data to international projects devoted to high data quality monitoring of the background air pollution in the Arctic. An approach for quantifying the influence of local and regional pollution on measurements that may be misinterpreted as long-range transported one, is presented here.

The hourly gas and aerosol data measured in Ny-Ålesund and at the Zeppelin station, respectively, have been analysed along with the meteorological data from Ny-Ålesund, Zeppelin station and Longyearbyen (south-east of Ny-Ålesund).

Seasonal fluctuation of the average measured values of SO_2 and NO_x has been observed. Three main wind directions coincided with the peak concentration of SO_2 and NO_x. The NW-N flow may bring local pollution from ship traffic and diesel power plant as well as biogenic SO_2 from the oxidation of DMS. The monthly average number of particles with diameter characteristic for ship plume (50–100 nm), was elevated for the hours when ships have been registered in the local call list. The number concentration of particles with diameter 200 nm, typical for Arctic haze events, and concentration of non-sea salt sulphate rise during springtime. The FLEXTRA-trajectory analysis indicated that most pollution brought by E-SE and SW flows may be of long-range and/or regional origin. Events with these flow directions need to be interpreted with caution.

Keywords: aerosol, Arctic, local pollution, long-range transport, trajectory.

1 INTRODUCTION

Nitrogen oxides NO_x, ($NO+NO_2$), and sulphur dioxide SO_2 are emitted in large amounts from combustion of various fossil fuels worldwide. Monks [1] among others stated that NO_x, in the presence of volatile organic compounds (VOC) and/or carbon monoxide CO, are responsible for the production of tropospheric ozone, O_3, through the photochemical reactions in urban smog. In turn, as was reported by the Intergovernmental Panel on Climate Change (IPCC) [2], tropospheric O_3 is an important greenhouse gas, and being a strong oxidant, it effects the concentration of other greenhouse gases. Moreover, both NO_x and SO_2 are acidifying agents, and, according to the Arctic Monitoring and Assessment Programme (AMAP) reports [3, 4], their deposition may have a strong negative effect on many terrestrial ecosystems, specifically vulnerable in the Arctic under rapidly changing climatic conditions, while the impact of emissions of acidifying agents from increasing shipping traffic in the Arctic on marine coastal ecosystems needs to be investigated.

Jacob [5] stated that the lifetime of NO_x is on the order of one day in the lower troposphere at mid-latitudes, and Lelieveld *et al*. [6] reported the lifetime of SO_2 and non-sea salt sulphate

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to be approximately 2 days and 5 days, respectively. Therefore, according to the "classic" air pollution literature, the sources of NO_x and SO_2 are mostly regional or local. Furthermore, in mid-latitudes, the local air pollution is mainly characterized by higher concentrations, while long-range transported pollution is considered to be more dispersed. However, physical conditions, such as low air temperatures and low humidity, limited turbulent mixing and the absence of sunlight during the polar night, as well as atmospheric dynamics, namely the position of the Arctic front, increase lifetime of pollutants during winter- and springtime Stohl [7]. Due to this, the lifetimes of NO_x and SO_2 were estimated by Beine *et al*. [8] and Lee *et al*. [9] as 10 days and 4 days north of the Arctic front, respectively.

During winter the Arctic front barrier, formed by the surfaces of constant potential temperature increasing with height, extends further south (up to 50°N). Consequently, according to Quinn *et al*. [10], in the winter and spring the Arctic haze, polluted air masses transported mainly from Europe and Asia, may be observed in polar regions. On the other hand, during summer the Arctic front is located further north and air may remain continuously north of 80°N in the lower troposphere up to 14 days. Results from several studies, [7,11,12], show that this prevents the transport of pollutants from Eurasia during this season, and local aerosol sources on Svalbard are considered to be more important during this time of the year.

Svalbard's archipelago is nearly a pristine Arctic environment with only a few local and regional anthropogenic pollution sources. Therefore, much of the atmospheric research activities there are devoted to the monitoring of long-range transported pollution in the Arctic.

The Zeppelin Observatory is the Norwegian atmospheric monitoring station situated on a mountain ridge 2 km away from a small research settlement Ny-Ålesund. The station is of high importance for the Global Atmosphere Watch, The European Monitoring and Evaluation Programme (EMEP), AMAP and many other research projects due to unique opportunities for monitoring of background air composition, meteorological and climatological studies.

The main purpose of this article is to discuss ambiguities related to the process of identification of possible sources of air pollution on Svalbard and present an approach for quantifying the influence of local and regional pollution on measurements in Ny-Ålesund.

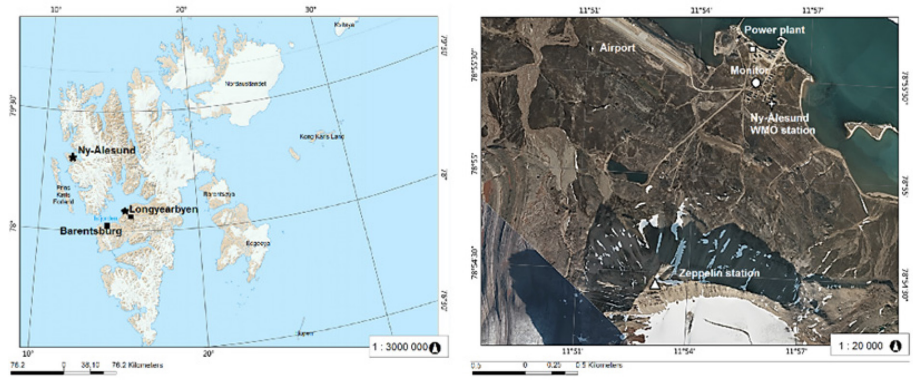
2 AIR POLLUTION SOURCES ON SVALBARD

Coal-fired power plants are operated in the two settlements of Longyearbyen and Barentsburg located to the south-east of Ny-Ålesund. According to Vestreng *et al*. [13], these are the largest year-round anthropogenic point sources of SO_2 in Svalbard. Both have seasonally variable emission rates, Fig. 1a.

According to the environmental impact assessment of Ny-Ålesund as an international scientific research and monitoring station (Shears *et al*. [14]), the power plant fuelled by low sulphur diesel, is the largest local year-round point source of NO_x in Ny-Ålesund. It too has seasonally variable emission rates. The monitoring station is installed south of the power plant, Fig. 1b.

In addition to this, combustion engines on tourist ships produce fumes that contain NO_x, SO_2 and particulate matter. Shears *et al*. [14] and Eckhardt *et al*. [15] noted that these summertime local sources of emissions have significant impact on atmospheric measurements in Ny-Ålesund. The impact rate depends on emission rates (ship's size and number of ships present in the fjord simultaneously) and atmospheric conditions.

The overview of the emissions from the main sources is given in Table 1. The emission rates for the first three sources and for the last two sources in the table are calculated from hourly and annual values defined in Shears *et al*. [14] and Miljødirektoratet [16], respectively.



(a) (b)

Figure 1: Study area: (a) map of Svalbard showing Barentsburg and Longyearbyen and meteorological stations as squares and stars, respectively, and (b) local map of Ny-Ålesund showing power plant, monitor, Ny-Ålesund WMO station and Zeppelin station as square, circle, star and triangle, respectively.

Table 1: Main sources of emissions in Ny-Ålesund and on Svalbard.

	Source	SO_2,·10^{-5} kgs^{-1}	NO_x,·10^{-5} kgs^{-1}
1	Diesel generators and central heating in Ny-Ålesund	32	117
2	Small ships in Ny-Ålesund	14	83
3	Cruise ships in Ny-Ålesund	1444	3889
4	Barentsburg power plant (average 2010–2013)	7191	447
5	Longyearbyen power plant (average 2009–2014)	1368	490

3 MATERIALS AND METHODS

The ground-based SO_2 and NO_x observations have been sorted according to the prevailing wind direction and compared with ship traffic statistics. When concentrations of SO_2 and NO_x were above a lower detectable limit (LDL), the FLEXTRA-trajectory model output was examined for distinguishing between local and long-range transport of pollutants. By analogy with Stohl [7], if air resided exclusively north of 70°N during the previous 7 days for trajectory arriving at altitude 500 m to the Zeppelin station, it was considered to be no long-range transport of pollutants (NLRT case). If the trajectory data were missing, or there were values of latitude <70°N, it was assigned as a possible long-range transport (LRT) case. According to Brock *et al*. [17], the sub-0.1-μm particles often prevail in the particle number population of aged coal power plant plumes several hours after the emission. In addition, experimental studies of Petzold *et al*. [18] show that the combustion particles have modal diameters centred at 50 nm and 100 nm for raw emissions and for a plume age of 1 hour, respectively. Therefore, the particle mode with d = 50–100 nm has been chosen to check the

possible year-round influence of coal power plant and summertime ship emissions on Zeppelin measurements.

3.1 Measurements description

The SO_2 and NO_x data were collected by Norwegian Institute for Air Research (NILU) during the project Local Air Quality Monitoring 2008–2010 in Ny-Ålesund [19] from 14.07.2008 to 24.08.2010. Both analysers used in the project, had LDL = 0.4 ppb. Most of the data have been below this value, which is too high for the near pristine environment of Ny-Ålesund. Therefore, the data equal to or higher than LDL have been considered as peaks in this work. The aerosol measurements presented here have been performed by Stockholm University at the Zeppelin station. The daily filter samples data collected by NILU at the Zeppelin station are part of the "Cooperative programme for monitoring and evaluation of long-range transmission of air pollutants in Europe" (EMEP). The non-sea salt sulphate has been defined according to the non-sea salt sulphate correction algorithm presented in the WMO report [20]. An overview of the chemical and aerosol data is shown in Table 2.

Combined analysis of ground-based hourly meteorological data from the monitor with gas analysers and Ny-Ålesund WMO station (78.9230 N, 11.9333 E), operated by NILU and Norwegian Meteorological Institute, respectively, provides coverage for the whole period of air quality measurements. In addition, data from the Zeppelin station and from the Svalbard lufthavn (Svalbard airport) (28 m a.s.l., 78.2453 N, 15.5015 E) have been used, Fig. 1a and b.

3.2 Model data description

The FLEXTRA 3D backward trajectories (www.nilu.no/trajectories) used in this study are provided by NILU. They run 7 days backward in time and are based on ECMWF (European Centre for Medium Range Weather Forecasts) meteorological data with spatial resolution of 1.25° and temporal resolution of 6 hours. The nearest trajectory to the time of the peak has been chosen, and when the peak value falls in between two trajectories both have been assessed. If at least one of them passed south of 70°N, then it was considered to be an LRT-case. The modelled data are available for the whole period of interest. Four percent of data is missing (most of the dates in December 2008 and several other discrete days in 2008). As reported by Stohl [26], the position errors in FLEXTRA are in the order of 20% of the travelled distance

Table 2: Data analysed in the paper.

Equipment and reference	Measured component and units	Location
Chemiluminescence NO_x analyser (model 200E) [21]	NO, NO_2, NO_x, $\mu g/m^3$	Monitor, 78.9247N, 11.9262E
UV Fluorescence SO_2 analyser (model 100E) [22]	SO_2, $\mu g/m^3$	
Condensation particle counters (TSI CPC 3025 and TSI CPC 3010) [23, 24]	Integral aerosol number density and size distribution, cm^{-3}	Zeppelin station, 78.9073N, 11.8859 E
Aerosol filter [25]	SO_4^{2-}(p), $\mu g\ S/m^3$	

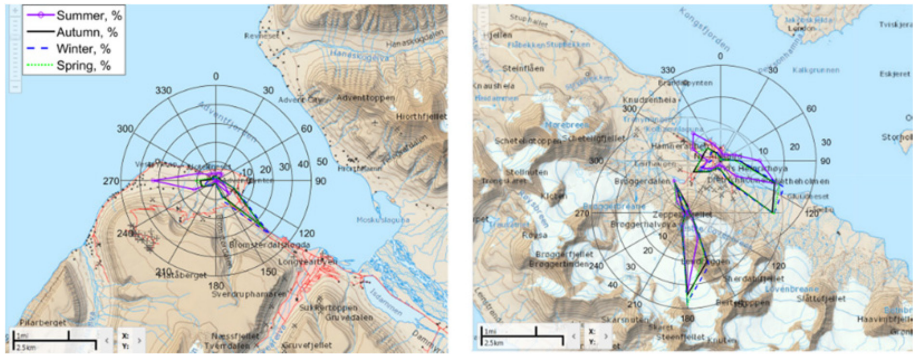


Figure 2: Seasonal wind roses: (a) Svalbard lufthavn station north-west of Longyearbyen and (b) Ny-Ålesund WMO (upper wind rose) and Zeppelin (lower wind rose) stations.

and the performance varies with the meteorological conditions, but the approximate pathway of the air mass may be estimated.

4 RESULTS AND DISCUSSION

The seasonal wind roses for the period of measurements are plotted (Fig. 2) for 16 wind directions (22.5° for each sector).

One can see that the prevailing wind direction differs significantly for summer at all stations comparing to other seasons. Most likely, the reason for this is that increasing temperature differences between the land and water facilitate the formation of on shore circulation. The lowest mean seasonal wind speed is observed in summer also. The seasonal wind speed rises gradually and is highest in winter likely due to enhancing influence of mesoscale cyclonic activity, as discussed in Maturilli *et al*. [27]. Additionally, the topographical wind channelling plays important role year-round at all three stations.

The change of wind direction and speed may influence the dispersion of pollutants. The plume from the power plant located to the south-east of the Svalbard lufthavn station in the Longyearbyen town may be trapped in the valleys nearby, Longyeardalen and Adventdalen, due to the prevailing westerly wind direction in summer (Fig. 2a). Therefore, this pollution source is unlikely to influence the measurement results in Ny-Ålesund during this season.

The Zeppelin station is located at the height of 474 m above sea level. The most frequently observed wind direction at the Zeppelin observatory is south and south-south-east due to shadowing effect of nearby mountains, Fig. 2b. From the wind roses for Ny-Ålesund and Zeppelin stations, one can see that the wind direction varies significantly, even within distance of 2 km, due to complex topography.

Analogously, although Longyearbyen and Barentsburg are located in the inner part of the same fjord, Isfjorden, the data from Svalbard lufthavn station most probably can't be utilized for assessment of spreading of pollution from Barentsburg power plant, and separate dataset for Barentsburg is needed (see Fig. 1a).

However, the on shore circulation may bring the pollution from the ships cruising in the Kongsfjorden or attached to pier in Ny-Ålesund in summer, Fig. 2b.

Indeed, despite only 31% and 8% of all NO_x and SO_2 hourly data being defined as peak, seasonal fluctuation of the average measured values of SO_2 and NO_x has been observed with increasing concentration of gases every summer and winter, Fig. 3. Mean SO_2 and NO_x concentrations and number of particles with d = 50–100 nm values were higher on 21%, 16% and 55%, respectively, for time interval of 2 hours before arrival to 2 hours after departure registered in the cruise call list comparing to hours without ships. Elevated values of SO_2 in presence of ships mainly coincide with NNW-N wind, which is natural, because the harbour is located north of the monitor (Fig. 1b). However, one peculiar feature of local pollution dispersion pattern has been revealed. Although there are glaciers 3 km south-west from monitor and, according to meteorological studies [27], wind from this direction is of katabatic origin, SW-WSW wind brings at times SO_2, NO_x and particles emitted by big anchored ships according to the cruise calls list. These cases are rare but they affect the mean summer concentration of SO_2 for this wind direction significantly. Mean NO_x concentrations were approximately five times higher year-round when NW-NNW wind had been observed due to emissions from diesel power plant north of the monitor in Ny-Ålesund.

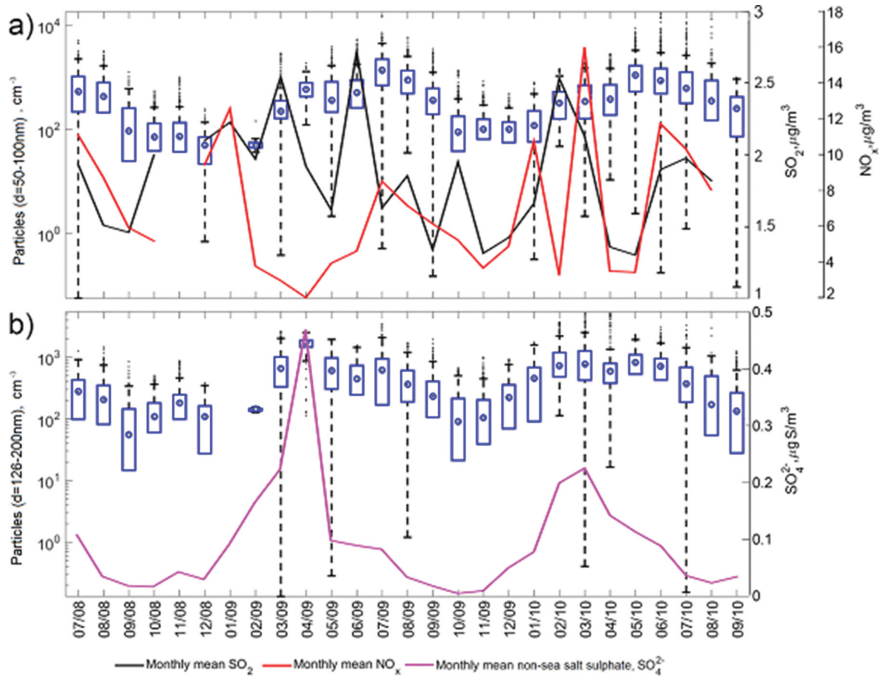


Figure 3: Monthly statistics of integral aerosol number density (box and whiskers plots) and gas analysers and filter samples data (lines): a) integral aerosol number density for particles with d = 50–100 nm, cm-3, and monthly mean SO_2 and NO_x from gas analysers, μg/m^3; b) integral aerosol number density for particles with d = 126–200 nm, cm-3, and monthly mean non-sea salt sulphate from filter samples, μg S/m^3. The logarithmic scale has been used for aerosol data (left y-axis on both figures). The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and statistical outliers are plotted individually on each box.

The integral aerosol number density of particles with size 10–40 nm increases every summer significantly, which indicates boundary layer nucleation events. High mean number of particles were at times observed for northerly wind direction and coincided with SO_2 peak even in absence of ships. This supports previous studies of fine particle composition performed by Heintzenberg and Leck [28] that revealed the importance of marine biogenic sources of sulphur compounds on Svalbard.

The concentrations of particles with size 50–100 nm decrease in wintertime and start increasing again in spring with the peak in summer, Fig. 3a. One possible reason for this is that there is no influence of coal power plant emissions on measurements in Ny-Ålesund. However, one may notice that the growth in particle number of this mode starts in February, when the polar night season on Svalbard is over, although there is still no direct sunlight. According to Brock *et al*. [17], the particulate sulphate formation in coal power plant plumes takes place mostly through oxidation of SO_2 by OH. The oxidation may occur in aqueous phase as well. However, both processes are restricted due to Arctic environmental conditions in winter, thus the number of particles of this mode is not an applicable parameter for determination of regional pollution on Svalbard in winter. The number of particles with diameter 126–200 nm rises during springtime, and similar pattern is observed for non-sea salt sulphate from filter samples collected at the Zeppelin station, Fig. 3b. This is in good agreement with Seinfeld and Pandis [29] who stated that the Arctic haze phenomena is the long-range transported polar aerosol consisting to a large extent of non-sea salt sulphate of anthropogenic origin.

The trajectory analysis revealed that during summer there is no difference in NO_x mean value whether it was a LRT or a NLRT case, and the concentration depends solely on the wind direction. Concentration decreases during autumn and spring, and mean NO_x value was higher for LRT cases. During winter, values of NO_x for NLRT cases are higher than for LRT ones, probably due to increasing of emissions from the diesel power plant because of enhanced fuel consumption and limited dispersion because of prevailing stable stratification of atmospheric boundary layer. SO_2 values for LRT cases were higher for winter and spring and lower than NLRT cases for autumn and summer. In general, the trajectory analysis indicated that most of pollution brought by E-SE and SW flows, 66% and 60%, respectively, may be of long-range and/or regional origin (possibly from two coal power plants located to SE from Ny-Ålesund). There were some cases in wintertime when trajectory analysis did not show possible long-range transport of pollution, however, elevated concentrations of SO_2 have been measured and SE wind direction has been detected both in Ny-Ålesund and at the Svalbard lufthavn station several hours earlier. Therefore, either there was influence of regional pollution from coal power plants, or modelled trajectory was erroneous. In order to check this, simple backward trajectory FLEXTRA-model results may be replaced in future work by Lagrangian particle dispersion model results, for example, FLEXPART, as it has been suggested by Stohl *et al*. [30] for more accurate interpretation of measured data. Additionally, case study modelling using a plume dispersion model may be done for the dates of interests for power plants in Longyearbyen and Barentsburg.

The changes in the amount of emissions from ships and power plants are expected. A three-stage treatment system of emissions to reduce NO_x, particles and SO_2 is planned to be installed in the Longyearbyen coal power. Barentsburg power plant has been stated as the biggest SO_2 source in Norway, it is currently operated with a permission for emissions of up to 2400 tons SO_2/year as reported by Norwegian Environmental Agency (Miljødirektoratet) [31]. As there is a high rate of uncertainty in the future emission scenarios for the power plants, field campaigns should be performed.

It is restricted to use heavy fuel in Ny-Ålesund since January 1, 2015, and only marine gas oil (MGO) with maximum sulphur content 1.5% is permitted. The emission restrictions will give a steep decline in the number of port calls by cruise ships. However, the NO_x and particle pollution may still be present in summer even if big ships will use MGO instead of heavy fuel. The present study should be continued to quantify the magnitude of improvement in air quality resulting from the emission restriction.

5 CONCLUSIONS

The air quality and meteorological data from Ny-Ålesund have been analysed concurrently. The distinct characteristics for the near pristine coastal Arctic site have been defined, such as seasonal patterns in prevailing wind direction and aerosol integral number density specific for different particle diameters and importance of long-range transported pollution.

FLEXTRA-trajectory analysis revealed that most of the total number of SO_2 peaks from SE and SW flow may be of long-range and/or regional origin with prevailing LRT cases during winter and spring.

During wintertime, there are no ships or biogenic sources in Ny-Ålesund and due to environmental conditions the oxidation of SO_2 to SO_4^{-2} is limited. Because of this, the long-range transport of SO_2 plays major role. However, the same conditions favour regional transport of sulphur dioxide from sources located SE from Ny-Ålesund due to prevailing wind direction. In addition, the fuel consumption at the coal power plants may increase during wintertime. The separation of LRT and regional emissions is therefore ambiguous. Data from Hornsund or Hopen could be very powerful agents to diminish this uncertainty in our ability to quantify the regional influence on the quality of the Ny-Ålesund data.

During summer, long-range transported pollution is less important. Despite decreased fuel consumption at the diesel and coal power plants, local pollution from ships in Ny-Ålesund has been significant during summer. However, analysis of integral aerosol number density of particles with size 10–40 nm and SO_2 data revealed that biogenic sulphur and ultrafine particle sources have to be taken into account also.

The Lagrangian particle dispersion and plume modelling may be done to clarify the pathways and environmental fate of regional pollution from coal power plants on Svalbard. The measurement campaign for sampling of the plume from the coal power plants in Barentsburg and Longyearbyen may be recommended to determine current rate and composition of emissions.

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REFERENCES

[1] Monks, P.S., Gas-phase radical chemistry in the troposphere. *Chemical Society Reviews*, **34**, pp. 376–395, 2005. http://dx.doi.org/10.1039/b307982c

[2] Hartmann, D.L., et al. Observations: atmosphere and surface (Chapter 2). *IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds., T.F. Stocker, et al, Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, pp. 159–255, 2013.

[3] Skjelkvåle, B.L. et al. Effects on freshwater ecosystems (Chapter 6). AMAP *Assessment 2006: Acidifying Pollutants, Arctic Haze, and Acidification in the Arctic*, Oslo, pp. 64–90, 2006.
[4] Bellerby R. et al. Acidification in the Arctic Ocean Region (Chapter 2). AMAP Assessment 2013: Arctic Ocean Acidification, Oslo, pp. 9–36, 2013.
[5] Jacob, D.J., *Introduction to Atmospheric Chemistry*, Princeton University Press: Princeton, NJ, pp. 211–215, 1999.
[6] Lelieveld, J., Roelofs, G.-J., Ganzeveld, L., Feichter, J. & Rodhe, H., Terrestrial sources and distribution of atmospheric sulphur. *Philosophical Transactions of the Royal Society B Biological Sciences*, **352**(1350), pp. 149–158, 1997. http://dx.doi.org/10.1098/rstb.1997.0010
[7] Stohl, A., Characteristics of atmospheric transport into the Arctic troposphere. *Journal of Geophysical Research*, **111**(D11), p. D11306, 2006. http://dx.doi.org/10.1029/2005JD006888
[8] Beine, H.J., Engard, M., Jaffe, D.A., Hoy, O., Holme, K. & Stordal, F., Measurements of NOx and aerosol particles at the Ny-Ålesund Zeppelin mountain station on Svalbard: influence of regional and local pollution sources. *Atmospheric Environment*, **30**(7), pp. 1067–1079, 1996. http://dx.doi.org/10.1016/1352-2310(95)00410-6
[9] Lee, C., Martin, R.V., Donkelaar, A.V., Lee, H., Dickerson, R.R., Hains, J.C., Krotkov, N., Richter, A., Vinnikov, K. & Schwab, J.J., SO_2 emissions and lifetimes: estimates from inverse modeling using in situ and global, space-based (SCIAMACHY and OMI) observations. *Journal of Geophysical Research*, **116**(D6), p. D06304, 2011. http://dx.doi.org/10.1029/2010JD014758
[10] Quinn, P.K., Shaw, G., Andrews, E., Dutton, E.G., Ruoho-airola, T. & Gong, S.L., Arctic haze: current trends and knowledge gaps. *Tellus B*, **59**(1), pp. 99–114, 2007. http://dx.doi.org/10.1111/j.1600-0889.2006.00238.x
[11] Zhan, J. & Gao, Y., Impact of summertime anthropogenic emissions on atmospheric black carbon at Ny-Ålesund in the Arctic. *Polar Research*, **33**, p. 21821, 2014. http://dx.doi.org/10.3402/polar.v33.21821
[12] Weinbruch, S., Wiesemann, D., Ebert, M., Schutze, K., Kallenborn, R. & Strom, J., Chemical composition and sources of aerosol particles at Zeppelin Mountain (Ny Ålesund, Svalbard): an electron microscopy study. *Atmospheric Environment*, **49**, pp. 142–150, 2012. http://dx.doi.org/10.1016/j.atmosenv.2011.12.008
[13] Vestreng, V., Kallenborn, R. & Økstad, E., Climate influencing emissions, scenarios and mitigation options at Svalbard, p.16, 2009.
[14] Shears, J., Fredrik, T., Are, B. & Stefan, N., Identification and prediction of environmental impacts (Chapter 8). *Environmental Impact Assessment. Ny-ålesund International Scientific Research and Monitoring station*, Svalbard, Tromsø, pp. 32–40, 1998.
[15] Eckhardt, S., Hermansen, O., Grythe, H., Fiebig, M., Stebel1, K., Cassiani1, M., Baecklund, A. & Stohl1, A., The influence of cruise ship emissions on air pollution in Svalbard – a harbinger of a more polluted Arctic? *Atmospheric Chemistry and Physics*, **13**(16), pp. 8401–8409, 2013. http://dx.doi.org/10.5194/acp-13-8401-2013
[16] Miljødirektoratet, Norske utslipp, available at www.norskeutslipp.no/

[17] Brock, C.A., Washenfelder, R.A., Trainer, M., Ryerson, T.B., Wilson, J.C., Reeves, J.M., Huey, L.G., Holloway, J.S., Parrish, D.D., Hubler, G. & Fehsenfeld, F.C., Particle growth in the plumes of coal-fired power plants. *Journal of Geophysical Research*, **107**(D12), pp. AAC 9–1–AAC 9–14, 2002.

[18] Petzold, A., Hasselbach, J., Lauer, P., Baumann, R., Franke, K., Gurk, C., Schlager, H. & Weingartner, E., Experimental studies on particle emissions from cruising ship, their characteristic properties, transformation and atmospheric lifetime in the marine boundary layer. *Atmospheric Chemistry and Physics*, **8**(9), pp. 2387–2403, 2008. http://dx.doi.org/10.5194/acp-8-2387-2008

[19] Hermansen, O., Wasseng, J., Backlund, A., Strom, J., Noon, B., Henning, T., Schulze, D. & Barth, V.L., Air quality Ny-Ålesund. Monitoring of local air quality 2008–2010. Measurement results, Kjeller, pp. 7–13, 2011.

[20] WMO, Manual for the GAW precipitation chemistry programme. *Guidelines, Data Quality Objectives and Standard Operating Procedures, in WMO Report*, **160**, ed M.A. Allan, pp. 159–160, 2004.

[21] Teledyne Advanced Pollution Instrumentation, Model 200E Nitrogen Oxide Analyzer, Technical Manual, San Diego, 2010.

[22] Teledyne Advanced Pollution Instrumentation, Model 100E UV Fluorescence SO2 Analyzer, Operation Manual, San Diego, 2011.

[23] TSI, Model 3010 Condensation Particle Counter, Instruction Manual, 2002.

[24] TSI, Model 3025A Ultrafine Condensation Particle Counter, Instruction Manual, 2002.

[25] EMEP, Sampling of sulphur dioxide, sulphate, nitric acid, ammonia, nitrate and ammonium using the filter pack method (Chapter 3.2). *EMEP Manual For Sampling and Chemical Analysis. Norwegian Institute for Air Research. EMEP CCC Report* **1/95**, Kjeller, pp. 3-13–3-28, 1996.

[26] Stohl, A., Computation, accuracy and applications of trajectories—a review and bibliography. *Atmospheric Environment*, **32**(6), pp. 947–966, 1998. http://dx.doi.org/10.1016/S1352-2310(97)00457-3

[27] Maturilli, M., Herber, A. & König-Langlo, G., Climatology and time series of surface meteorology in Ny-Ålesund, Svalbard. *Earth System Science Data*, **5**(1), pp. 155–163, 2013. http://dx.doi.org/10.5194/essd-5-155-2013

[28] Heintzenberg, J. & Leck, C., Seasonal variation of the atmospheric aerosol near the top of the marine boundary layer over Spitsbergen related to the Arctic sulphur cycle. *Tellus B*, **46**, pp. 52–67, 1994. http://dx.doi.org/10.1034/j.1600-0889.1994.00005.x

[29] Seinfeld, J.H. & Pandis, S.N., *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*, 2nd edn., John Wiley & Sons, Inc, pp. 378–379, 2006.

[30] Stohl, A., Eckhardt, S., Forster, C., James, P., Spichtinger, N. & Petra, S., A replacement for simple back trajectory calculations in the interpretation of atmospheric trace substance measurements. *Atmospheric Environment*, **36**(29), pp. 4635–4648, 2002. http://dx.doi.org/10.1016/S1352-2310(02)00416-8

[31] Sørby, H. & Sørmo, G., Tillatelse til virksomhet etter svalbardmiljøloven for Trust Arcticugol, Barentsburg, Miljødirektoratet, Trondheim, pp. 5–13, 2010.