Norsk institutt for luftforskning
Norwegian Institute for Air Research

Iceland Liechtenstein Norway grants

Monitoring atmospheric composition and deposition in Norway

Wenche Aas, Pernilla Bohlin-Nizzetto, Claudia Hak,
Katrine Aspmo Pfaffhuber, Hilde Uggerud

NILU report 7/2022

NILU report 7/2022	ISBN: 978-82-425-3076-9 ISSN: 2464-3327	CLASSIFICATION: A – Unclassified (open report)
DATE 15.03.2022	SIGNATURE OF RESPONSIBLE PERSON Ole-Anders Braathen (sign.) Deputy director	NUMBER OF PAGES 23
TITLE Monitoring atmospheric composition and deposition in Norway		PROJECT LEADER Cristina Guerreiro NILU PROJECT NO. O-120159
AUTHOR(S) Wenche Aas, Pernilla Bohlin-Nizzetto, Claudia Hak, Katrine Aspmo Pfaffhuber, Hilde Uggerud		QUALITY CONTROLLER Cristina Guerreiro
REPORT PREPARED FOR The State Treasury – Chief Inspectorate for Environmental Protection (GIOS) Bitwy Warszawskiej 1920 r. 3, PL-02-362 Warsaw, Poland Department of the Environmental Monitoring Al. Jerozolimskie 92, PL-00-807 Warsaw, Poland		CONTRACT REF. Barbara Toczko, b.toczko@gios.gov.pl

ABSTRACT

The Norwegian monitoring programme is set up to meet national and international obligations and needs for measurement data with a long-term commitment. The data are important for compliance monitoring as well as input for effect studies. The monitoring of atmospheric composition and deposition are organised under national programmes mainly funded by the Norwegian Environment Agency in addition to some direct support from the Ministry of Climate and Environment. NILU – Norwegian Institute for Air Research is responsible for the daily operation and reporting of the results from this monitoring. The monitoring aim to fulfil several inter-connected purposes and is divided in four main programmes: transboundary fluxes, contaminants, climate change and the ozone layer. In addition, regularly moss surveys are conducted to assess atmospheric deposition of pollutants such as heavy metals. The report was made for the project "Strengthening of atmospheric deposition assessment in Poland based on Norwegian experience" under the program "Environment, Energy and Climate Change", financed by the European Economic Area Financial Mechanism 2014-2021".

NORWEGIAN TITLE

Overvåkning av atmosfærens sammensetning og avsetning i Norge

KEYWORDS

Atmosphere and Climate | Deposition | Monitoring

ABSTRACT (in Norwegian)

Det norske overvåkingsprogrammet er satt opp for å møte nasjonale og internasjonale forpliktelser og behov for måledata med et langsiktig perspektiv. Dataene er viktige for å bevokte overholdelse av avtalte utslippsreduksjoner samt viktig grunnlagsdata for effektstudier. Overvåkningen er organisert under nasjonale programmer i hovedsak finansiert av Miljødirektoratet i tillegg til noe direkte støtte fra Klima- og miljødepartementet. NILU – Norsk institutt for luftforskning har ansvar for den daglige driften og rapporteringen av resultatene fra denne overvåkningen. Overvåkningen oppfyller flere sammenhengende fagområder og er delt inn i fire hovedprogrammer: grenseoverskridende luftforurensinger, miljøgifter klimaendringer og ozonlaget. I tillegg gjennomføres det jevnlig moseundersøkelser for å undersøke atmosfærisk avsetning av forurensninger som tungmetaller. Denne rapporten ble laget for prosjektet "Strengthening of atmospheric deposition assessment in Poland based on Norwegian experience" under programmet "Environment, Energy and Climate Change", finansiert av European Economic Area Financial Mechanism 2014-2021".

PUBLICATION TYPE: Digital document (pdf)	COVER PICTURE: Source: NILU

Citation: Aas, W., Bohlin-Nizzetto, P., Hak, C., Pfaffhuber, K. A., Uggerud, H. (2022). Monitoring atmospheric composition and deposition in Norway. (NILU report 7/2022). Kjeller: NILU.

NILU's ISO Certifications: NS-EN ISO 9001 and NS-EN ISO 14001. NILU's Accreditation: NS-EN ISO/IEC 17025.

Contents

1 Introduction 4

2 Measurement in the national regional monitoring programmes 6
2.1 Introduction 6
2.2 Deposition of sulfur and nitrogen 7
2.3 Particulate matter 10
2.4 Ground-level ozone 11
2.5 Contaminants 12
2.6 Compliance with international obligations 14

3 Moss surveys 17

4 Monitoring of aerosol properties, ozone layer, ozone depletion and climate gases. 19

5 Monitoring in urban environment 19

6 Final remarks 21

7 References 22

Monitoring atmospheric composition and deposition in Norway

1 Introduction

The Norwegian monitoring programme is set up to meet national and international obligations and needs for measurement data, with a long-term commitment. The data are important for compliance monitoring as well as input for effect studies: effects on health, terrestrial and aquatic environment, climate, and ozone layer. The observations are broadly used by the scientific community, national environmental authorities and for policy-making.

In Norway the regional and global monitoring of atmospheric composition and deposition are organised under national programmes mainly funded by the Norwegian Environment Agency in addition to some direct support for the Ministry of Climate and Environment. NILU – Norwegian Institute for Air Research is responsible for the daily operation and reporting of the results from this monitoring. The monitoring aim to fulfil several inter-connected purposes and is divided in four main programmes: transboundary fluxes (Aas et al., 2021), contaminates (Nizzetto et al., 2021), climate change (Myhre et al, 2020) and the ozone layer (Svendby et al., 2021). In addition, there is a monitoring programme specific for assessing the pollution close to the Russian border (Berglen et al, 2021). Further, nationwide moss surveys for trace metals have been conducted at regular intervals since 1977, the last one in 2015 (Steinnes et al., 2015).

The objectives of the different monitoring programmes requires different spatial resolution depending on lifetime of the species and the complexity in the monitoring techniques. The overall strategy is to co-locate measurements with many different components at a few sites for in-depth understanding of atmospheric processes. This is supported by several sites with only basic monitoring of some species to gather information of regional differences, especially important in Norway with quite large meteorological variations across the country. An overview of the regional sites and their measurement programme is found in Figure 1, left.

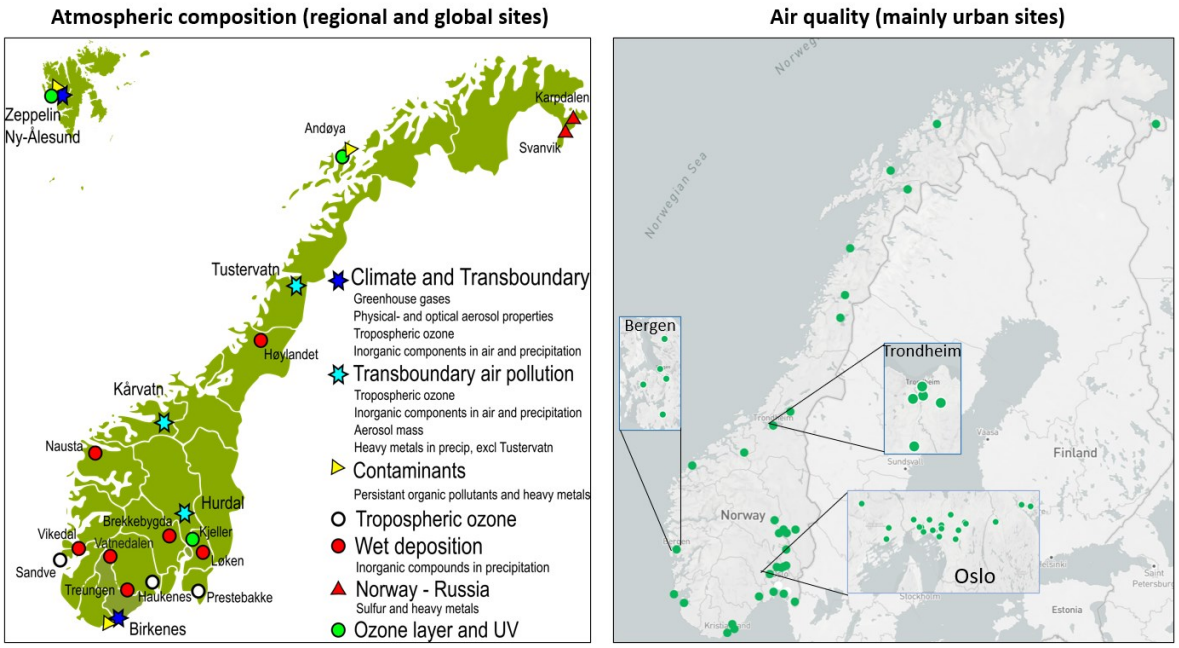


Figure 1: Overview of the Norwegian monitoring sites for atmospheric composition and deposition (left), and for air quality (right), 2021.

All the sites with atmospheric chemical composition measurements are located in rural areas and are believed to generally give good estimates of long range transported pollutants. In regions with local sources such as emissions from industry, traffic or agriculture, pollutant levels may be significantly higher. The monitoring of air quality in urban and industrial areas are on the other hand set up to monitor where there is highest pollution (Figure 1, right). These sites mainly include observations of particulate matter (PM) and NO, which in Norway are those of highest concern regarding health effects. The monitoring of air quality is conducted by the different municipalities, reported to a national data repository and quality controlled by the national reference laboratory (hosted at NILU).

The Norwegian monitoring programmes are built upon international obligations given by several conventions, protocols, frameworks, and directives in addition to national priorities with special focus on the sensitive Arctic environment. Below is a list of relevant organisations and frameworks which define commitments and guidelines as well as recommendations of methodologies and reporting. Whether the Norwegian program fulfil the obligations are discussed in more details in chapter 2.6.

- Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP)
- International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) and integrated monitoring (ICP-IM) under UNECE-LRTAP
- Comprehensive Atmospheric Monitoring Programme (CAMP) under OSPAR (the Convention for the Protection of the marine Environment of the North-East Atlantic.
- Arctic Monitoring and Assessment Programme (AMAP)
- The World Meteorological Organization (WMO) Global Atmosphere Watch programme (GAW)
- European Environmental Agency (EEA) and the different EU air quality directives
- The Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS)
- Integrated Carbon Observation System (ICOS)
- The Advanced Global Atmospheric Gases Experiment (AGAGE)
- The Minamata Convention on Mercury under UNEP
- The Global Monitoring Programme (GMP) of the Stockholm Convention on Persistent Organic Pollutants (POP) under UNEP
- The Montreal Protocol on Substances that Deplete the Ozone Layer under UNEP

Several of these programmes share database infrastructure. All the Norwegian regional data are openly available at http://ebas.nilu.no. The urban observations, in addition to tropospheric ozone, are available at http://www.luftkvalitet.info, these data are also reported and made available by EEA.

In addition to the continuous monitoring, there are regular campaigns and projects. For deposition it is especially two programmes that are important:

- Moss survey on trace elements and organic pollutants (Schlabach et al. 2016, Steinnes et al. 2016).
- Total sulfur and nitrogen deposition to be used for 5-year average critical load assessments (Aas et al, 2017).

2 Measurement in the national regional monitoring programmes

2.1 Introduction

Long-range atmospheric transport contributes significantly to the deposition of air pollutants in Norway. Sulfur emissions on the European continent and in UK caused acid deposition in Norway with large consequences on the aquatic and terrestrial environment. To document the link between long range transport of air pollution, deposition and effect, NILU started routine sampling of precipitation and air in background areas on a daily basis in 1971, with sites located in the southernmost parts of Norway. These observations were coordinated through a project funded by the Organisation for Economic Cooperation and Development (OECD, 1977), a coordinated research effort during the period 1972–1977 to study long range transport of air pollutants.

Table 1: Measurement programme at Norwegian background stations in 2020, excluding measurements of climate gases and the ozone layer. Sites in italic are not regional representative sites.

	Air							Precipitation				Data reported to international programmes
	Hourly		Daily		Weekly		2d per week/ month	Daily	Weekly			
Site	Met	O_3	main	NO_2	PM + EC/OC	HM.	POPs	main	main	HM	POPs	
Birkenes	X	X	X	X	X	X[b,c]	X[d]	X		X[b]	X[e]	EMEP, ICPs, CAMP
Vatnedalen									X			
Treungen									X			
Haukenes		X										
Prestebakke		X										EMEP
Løken									X			
Hurdal	X	X	X	X	X			X		X[a]		EMEP, ICP-Forest
Brekkebygda									X			ICP-IM
Vikedal									X			CAMP
Sandve		X										EMEP
Nausta									X			CAMP
Kårvatn		X	X	X	X			X		X[a]		EMEP, ICP-IM, CAMP
Høylandet									X			
Tustervatn		X	X	X				X				EMEP
Andøya*						X[b,c]	X[f]					EMEP, AMAP, CAMP
Karpbukt						X[b,c]			X	X[b]		
Svanvik						X[b,c]				X[b]		
Zeppelin	X	X	X			X[b,c]	X[g]					EMEP, AMAP, GAW
Ny-Ålesund									X			CAMP
Total number	3[+]	7+1	5	4	3	3+2	3	4	9	3+2	1	

* Will be closed down in 2022. [+]it should be noted that the Norwegian meteorological service do has observation closely at several sites

Met. = meteorology (wind direction, pressure and temperature)
main.precip = amount (mm), pH, conductivity, SO_4, NO_3, Cl, NH_4, Ca, K, Mg, Na
main air = SO_2, SO_4, $HNO_3 + NO_3$; $NH_4 + NH_3$, Ca, K, Mg, Na, Cl
HM [a] = Pb, Cd and Zn (includes Hg from 2021)
[b] = As ,Cd, Cr, Co, Cu, Pb, Mn, Ni, V, Zn and Hg (Not Hg at Karpukt and Svanvik).
[c] = Al, Fe, Ti
POPs [d] = α- og γ-HCH, HCB, DDTs, PCBs, PBDE, HBCD, PAHs, PFAS, Siloxanes, SCCP, MCCP
[e] = α- og γ-HCH, HCB, PCB,
[f] = HCB, PFAS
[g] = α- og γ-HCH, HCB, DDTs, Chlordanes, PCBs, BDE, HBCDs, PAHs, PFAS, Siloxanes, SCCP, MCCP

A national monitoring programme organized by the Norwegian Environment Agency was initiated in 1980, and the national programme become also part of the Monitoring and Evaluation Programme (EMEP, Tørseth et al 2012) following the previous mentioned OECD project. The EMEP observations include measurements of species linked to acidification, eutrophication, photochemical oxidants, heavy metals, persistent organic pollutants (POPs), and particulate matter. Most of the substances included in the EMEP monitoring program are also fundamental for improving the knowledge of climate change and both local and urban air quality.

Several changes in the content of the measurement programme, as well as in the number and distribution of monitoring sites, has taken place during the 40 years life-time of this monitoring programme. Since around 2010 the has been relatively small changes. The present monitoring programme is presented in Table 1 and reported to the Norwegian Environmental Agency annually (Aas et al., 2021 and Nizzetto et al., 2021).

2.2 Deposition of sulfur and nitrogen

There are thirteen sites measuring major ions in precipitation, while 5 of these are also measuring these in air, four at the mainland (Table 1, Figure 1). These four sites have daily sampling as recommended by the EMEP programme (EMEP 2019). The other sites with weekly observations are not reported to EMEP, but two of these are part of the CAMP programme where weekly resolution is ok. Some of sites are also part of GAW, AMAP and the two ICP programmes (Table 1). All the sites are however part of the national program for atmospheric deposition of sulfur and nitrogen species, and the data are reported and available from the same database infrastructure (EBAS).

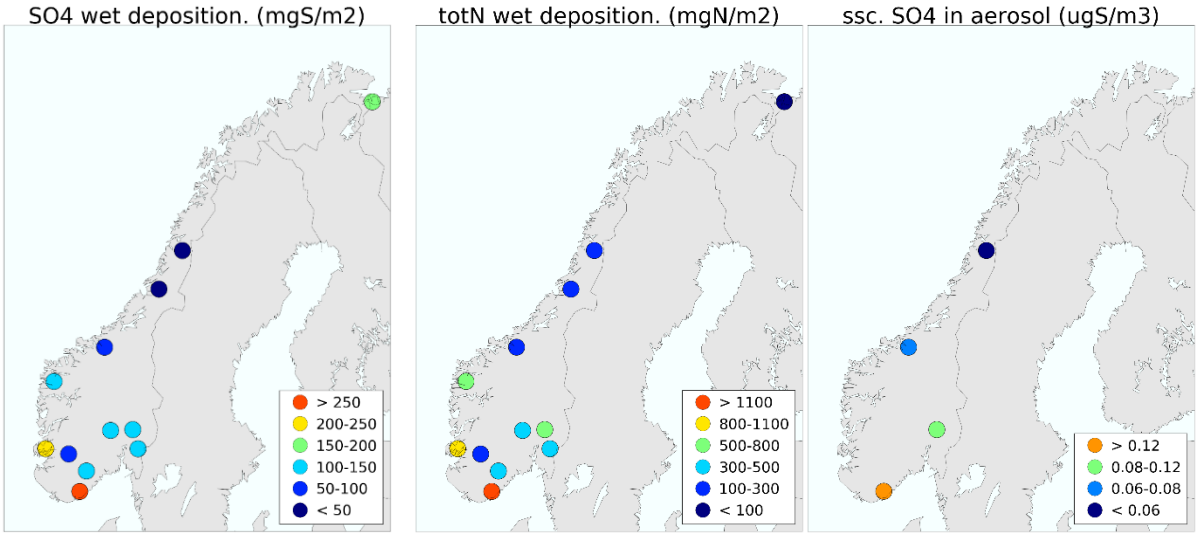


Figure 2: Wet deposition of sulfate (left), sum of nitrate and ammonium (middle) and air concentration of sulfate at Norwegian background stations in 2020. (Aas et al. 2021). Note that observations from the observations at Spitsbergen is not included in the maps.

These observations are used to estimates the total dry deposition of sulfur and nitrogen compounds and the measured wet deposition at the sites with both precipitation and air measurements of all the necessary sulfur and nitrogen components, Figure 3.

Dry deposition is calculated on the basis of the mean concentrations of SO_2, SO_4^2, NO_2, sum of nitrate (NO_3^- + HNO_3), and sum of ammonium (NH_3 + NH_4^+) and seasonal dry deposition velocities from literature. (Aas et al 2021). The dry deposition velocities of gases and particles are highly variable and uncertain quantities, and this simple method gives only a crude estimate of the dry deposition. But the

wet deposition contributes to around 80% depending on season and location and the uncertainties in the total loads are therefore less uncertain.

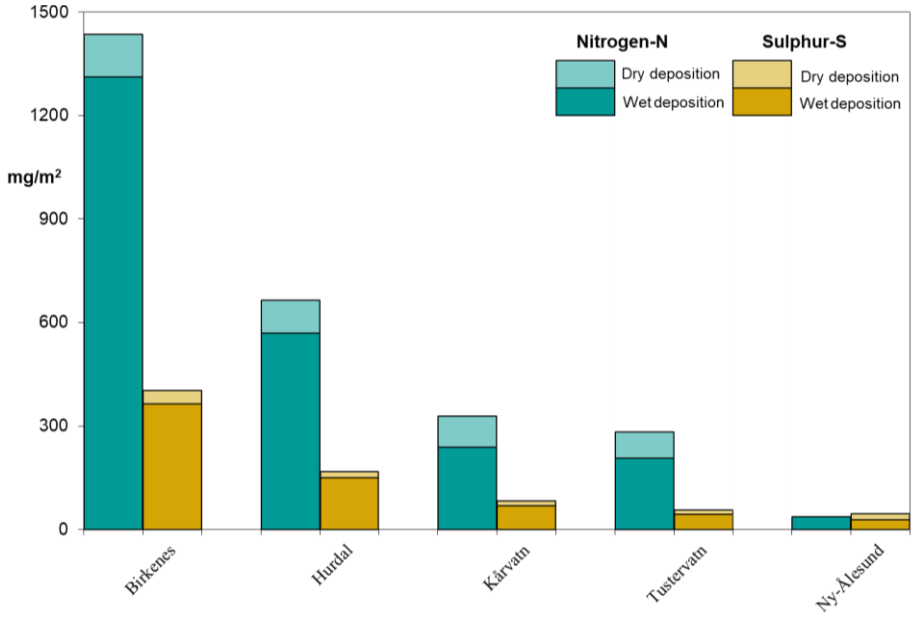


Figure 3: Total deposition (wet+ dry) of sulfur-S (SO_2, SO_4^{2-}) and nitrogen-N (NO_2, NH_4^+, NH_3, NO_3^-, HNO_3) at Norwegian background stations 2020.

In order to evaluate the exceedance of critical loads to the ecosystems, these site-specific depositions are not sufficient. It is necessary to interpolate and estimate the deposition with a high spatial resolution to reflect on the available information on spatial variation of the land surface (vegetation, soil and aquatic environment). In Norway we are using two different approaches:

1) from measurements of air and precipitation chemistry combined with statistical interpolation
2) combine observations and atmospheric model calculations, often called data assimilation or data-model fusion.

These depositions are combined to five-year average to get less affected by annual variations.

For both methods, data from the regular Norwegian monitoring network (Table 1) are combined with concentrations in precipitation and air from the Swedish, Danish, Finnish and Russian EMEP stations to get better information of deposition along the border. The precipitation amount data used for the calculations of the wet deposition is taken from the national meteorological observation network (MET) in addition to the NILU sites. Data from in total 300 automatic meteorological sites. Figure 4 gives and overview of the sites used in this assessment done on a five-year interval.

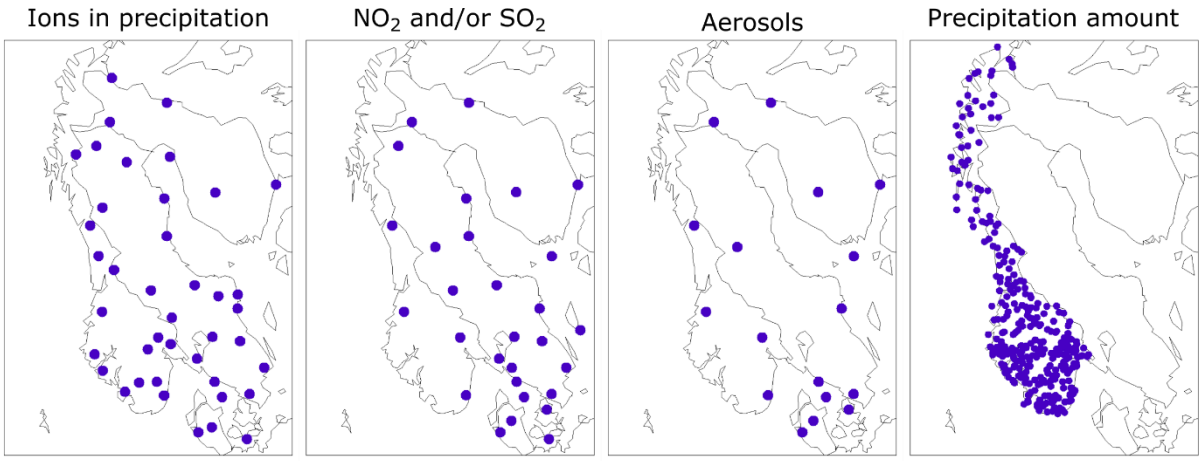


Figure 4: Overview of the sites used in estimating the deposition of sulfur and nitrogen for the period 2012-2016 (Aas et al, 2017).

In method 1) the concentrations in precipitation and air are interpolated from fixed sites to a regular grid of 50×50 km^2 using linear "kriging". Annual wet deposition was calculated at each site with precipitation amount multiplied with the interpolated concentration in the respective grid cell. And dry deposition was calculated on a 50x50 grid with estimated dry deposition velocity for each grid depending on surface type multiplied with the interpolated concentration in the grid. The total deposition estimated at each meteorological sites are visualized using standard interpolation routines, illustrated with sulfur deposition in Figure 5.

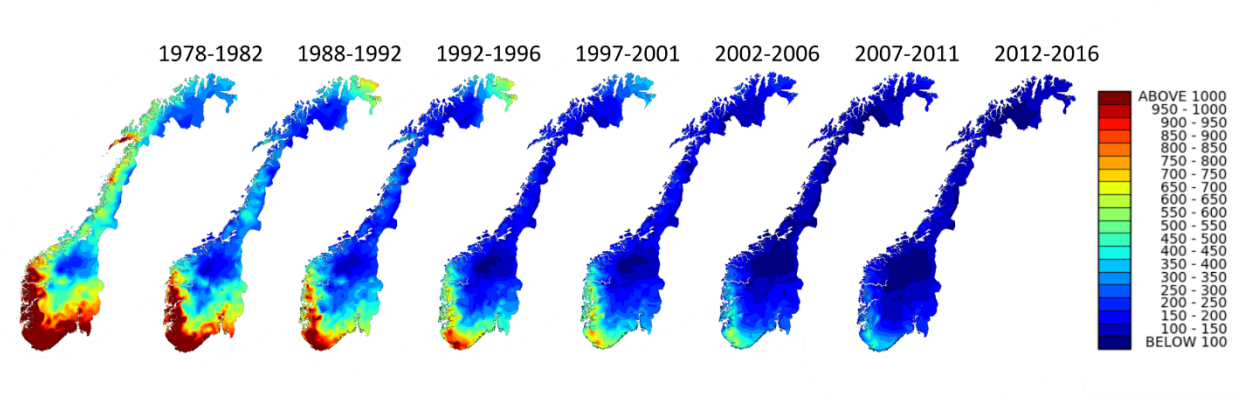


Figure 5: Trend in deposition of non sea salt sulfur in Norway (mgS/m^{2}y) (Aas et al, 2017), calculated using observation based method.

There are two main limitations with traditional observational based method 1). Firstly, at the Norwegian mainland, there are currently only 12 regional sites with precipitation chemistry and 4 with gas and aerosols measurements. Thus, there are large areas of Norway where these sites not necessarily are representative, and the uncertainty in the interpolation between these sites is large. Secondly, the dry deposition is not measured directly, and it is necessary to estimate the deposition velocities based on literature values combined with information on climatic conditions and ground cover. These are very crude estimates, both spatially and temporally and do not take into account the interaction between species, i.e., co-deposition.

The atmospheric chemical transport models usually have a much higher spatial and temporal coverage and can potentially fill the gaps and limitations of the observational based method. In Norway we have used the dispersion model developed by the Norwegian Meteorological Institute (MET) under the Co-

operative programme for monitoring and evaluation of long-range transmissions of air pollutants in Europe (EMEP) (Simpson et al., 2012). These model calculations have been combined with observations for the period 2012-2017 (Aas et al, 2017).

In the combined model and observation method 2), the model results are adjusted by the observations giving large weight to the observed values close to stations and using the modelled values in areas with no observations. The dry deposition rates are taken from the EMEP model using the monthly averages for each species specified for each grid cell.

The two methods are comparable and resemble the same general pattern of deposition throughout the country with higher deposition closer to the main emission sources in Europe, but with some regional differences. The combined method improves the spatial information of the deposition pattern and for wet deposition. For dry deposition there are quite large uncertainties in the estimated dry deposition velocities in both methods. Further, there are also quite large uncertainties in the observations as well as the reported emissions of especially NH_3. The relatively few sites, especially for air components, make it difficult to estimate the distance of influence of the measurements when adjusting the model results It is recommended to further explore improvement in the combined method to give more confidence in especially the dry deposition processes (Aas et al 2017).

A third way of measuring deposition is by using the throughfall method as done by ICP Forest. In Norway, there are three ICP Forest sites: Birkenes, Hurdal and Osen (Timmermann et al, 2020). The sulfur deposition from throughfall is quite comparable with what is estimated using wet+dry deposition at the Norwegian sites. For nitrogen deposition it is larger deviation probably due to the difficulties estimating the interaction between nitrogen and the canopy, i.e uptake and leaking from the canopy, Figure 6.

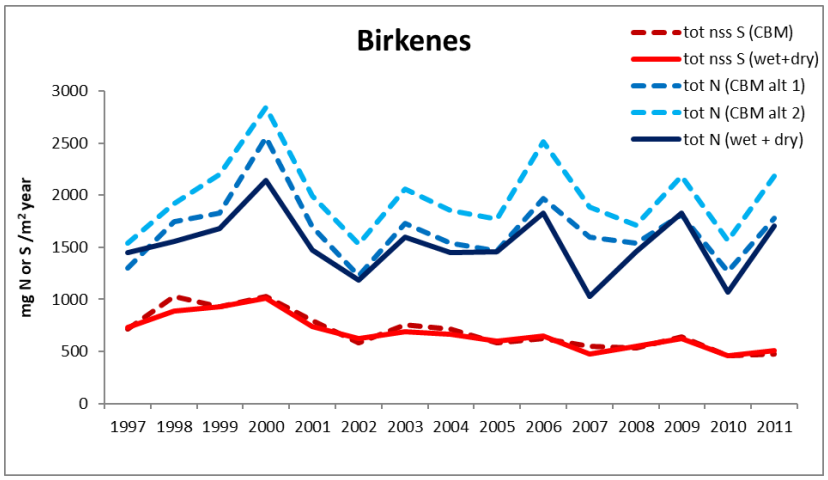


Figure 6: Comparing total deposition of sulfur (red) and nitrogen (blue) using the observations of precipitation and air concentration (wet + dry) with the throughfall measurement combined with canopy budget model (CBM) at Birkenes.

2.3 Particulate matter

Monitoring of the PM_{10} and $PM_{2.5}$ mass concentration takes place at three rural background sites; the Birkenes Observatory and the Hurdal and Kårvatn sites (Table 1). The time series at Birkenes dates to 2000/1, whereas measurements were initiated in 2010 at the two other sites. At Birkenes, high time resolution measurement of the aerosol size distribution for the size range 0.02 – 10 µm, was initiated in 2010, whereas high time resolution measurements of PM_{10} started in 2017. EC and OC were measured in the PM_{10} and $PM_{2.5}$ size fractions at all the sites. Combining the observation of secondary

inorganic aerosols (SIA) described in chapter 2.2, it is possible to assess the chemical composition in PM_{10}. In Figure 7 is an example of this at Birkenes for 2020 as well as the trend of PM since 2001.

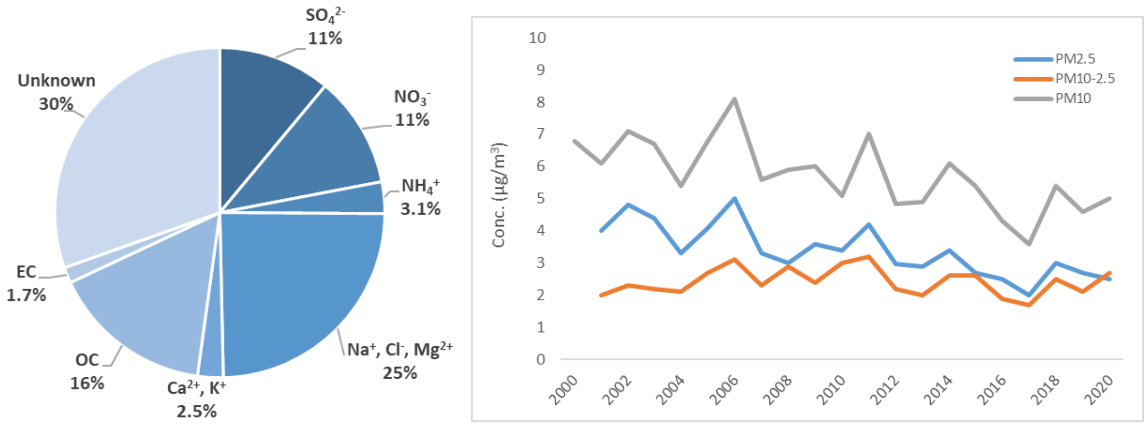


Figure 7: Annual mean chemical composition of PM_{10} (left) and trends in annual concentration of PM at the Birkenes Observatory (right).

Source apportionment studies (Yttri et al.,2021) show that natural sources dominate OM in PM_{10} at Norwegian rural background sites in summer, with biogenic secondary organic aerosol (BSOA) being the major source followed by primary biological aerosol particles (PBAP), whereas wildfires occasionally make a noticeable contribution.

2.4 Ground-level ozone

Measurements of ozone has been going on in Norway since 1975, first in Telemark and from 1977 also around the Oslo fjord and in subsequent years extended to the whole country. EU's air quality directive (AQD) (EU, 2008) which is implemented in Norwegian legislation contains the thresholds and objectives regarding ozone levels and the requirements as to the number of monitoring sites. The ozone monitoring network in 2019 consisted of eight stations. Seven of these were operated by NILU, while the Porsgrunn municipality was operating the station at Haukenes. The station at Haukenes can be classified as suburban while the rest are rural background stations which implies that the sites are not affected by local emissions. The ozone network is setup to as far as possible be able to assess its negative impacts on health and vegetation in Norway.

In Norway summertime episodes of elevated ozone are often associated with a high pressure located over the European continent, typically over Central or Eastern parts, setting up a southerly or southwesterly transport of warm, polluted air masses to the country. Ozone episodes are typically a fair-weather phenomenon associated with hot and sunny days. Furthermore, the highest ozone levels are often experienced just at the end of such fair-weather periods which is explained by an approaching cold front setting up an effective transport of photochemically processed air masses from the continent.

Various air quality criteria for ozone for the protection of health and critical levels for vegetation are given by WHO, EU, UNECE as well as national guidelines. The exposure related to these thresholds and guidelines are annually reported to the Norwegian Environment Agency (Aas et al 2021) as well as to EU and EMEP. I.e., the 3-months AOT40 values based on the definition in the EU directive for the years 2000-2020 is shown in Figure 8. The long-term objective of 3000 ppb hours has been exceeded for some years at several sites, illustrating the relatively large interannual variability in the ozone levels.

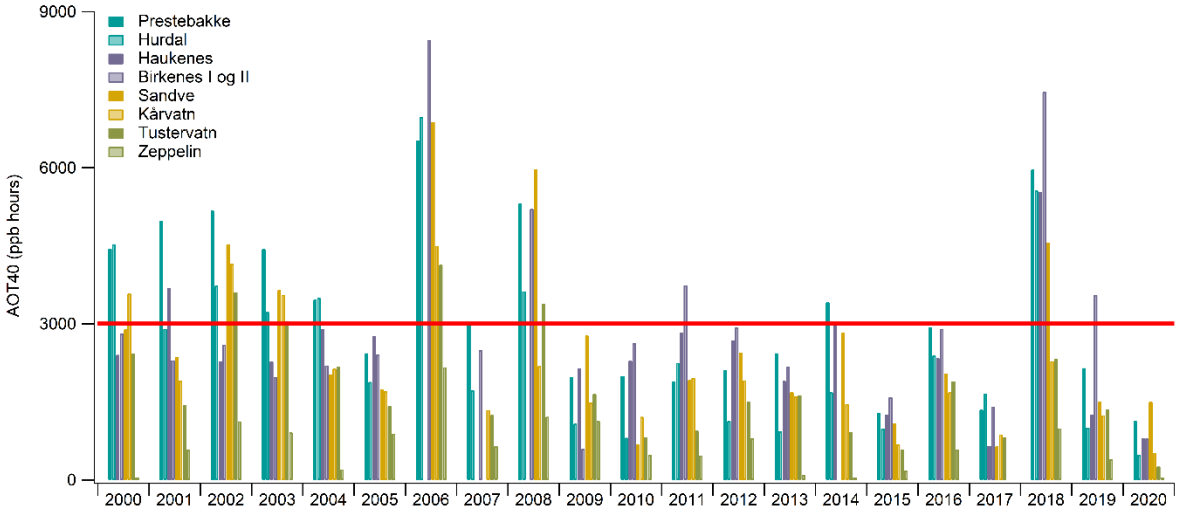


Figure 8: Annual 3 months' AOT40 values (1 May - 31 July) for the years 2000 - 2020 (based on UN-ECE's definition of daylight hours). The EU directive's long-term objective of 3000 ppb hours is indicated by the line. Note that the Birkenes site has been moved, and data before 2010 refer to the old location.

Research in recent years have shown that the AOT40 based critical levels for vegetation should be replaced with the so-called flux based critical levels when assessing the actual impact on plants (Mills et al., 2011). The flux-based levels (named POD_Y) takes into account various environmental conditions such as soil moisture, solar radiation, leaf area, vertical stability of the atmosphere, land cover etc, and thus provides a better estimate of the real ozone exposure of the plants. Comparison between AOT40 based levels and POD_Y levels with ozone exposure experiments in the field have indeed confirmed that the flux approach is better suited for direct assessments of the actual effect from ozone on vegetation. Concentration based AOT40 values continue to be used, however, where the meteorological data and calculations from flux models are not available, which is the case for Norway.

2.5 Contaminants

Monitoring of contaminants is of high priority for Norwegian authorities due to their harmful impacts on human health and/or on the environment together with their transboundary nature. For many of these contaminants, long-range transport via air is the most important source to pollution in remote areas where there are few or no local sources.

Air measurements of POPs and heavy metals including mercury started in 1991 at Lista observatory in southern Norway as part of a government program on environmental monitoring and were reported to the CAMP Programme. Lista was closed in 2004, but the extended measurement programme continued at the nearby observatory in Birkenes. In 1994, air measurements of heavy metals and POPs were included at the Zeppelin Observatory at Svalbard as part of the AMAP. Birkenes and Zeppelin became part of EMEP in 1999 (Tørseth et al., 2012). In the end of 2009, a new monitoring station was established at Andøya as part of the national Marine Pollution Monitoring Programme for the Norwegian Environment Agency (Green et al., 2011). This site will be closed down in 2022. Thus per 2021, active air sampling is conducted at three sites, while monitoring of heavy metals in precipitation are conducted at five sites, however two of these are part the program at the Russian border to assess pollution from the smelters Nikel. One site includes monitoring of mercury and POPs in precipitation. Location and measurement program is given in Figure 1 and Table 1, details and results are reported by Nizzetto et al. (2021).

A number of regulated POPs and POP-like substances have been monitored in air for about 20 years or more being part of the EMEP, CAMP and AMAP programmes: Hexachlorobenzene (HCB), hexachlorohexanes (HCHs), dichlorodiphenyltrichloroethane (DDTs), chlordanes polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs). Long-term data is also available for HCHs and HCB in precipitation from Birkenes. For some compounds the air monitoring has been performed for shorter time-periods than 15 years (i.e. 11 to 15 years), and monitoring started after Stockholm Convention came into force; polybrominated diphenyl ethers (PBDEs), hexabromocyclododecanes (HBCDs), and ionic per- and polyfluorinated alkyl substances (PFAS). Cyclic volatile methylsiloxanes (cVMS) and short- and medium chain chlorinated paraffins (SCCPs and MCCPs), have been monitored since 2013. Four groups of non-regulated organic contaminants of emerging concern was included in the monitoring programme at Zeppelin in 2017: novel brominated flame retardants (nBFRs), organophosphorous flame retardants (OPFRs), phthalates and volatile PFAS.

At Birkenes, Andøya and Zeppelin the monitoring programme includes all the eight priority elements in EMEP: lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), nickel (Ni), zinc (Zn), copper (Cu) and arsenic (As). In addition, the measurements also include aluminium (Al), cobolt (Co), manganese (Mn), iron (Fe), titanium (Ti) and Vanadium (V). Several of these originate from mineral dust and are used as tracers to assess the contribution of air pollution from this source.

Figure 9 illustrated the long-term trends of POPs and mercury in precipitation at Birkenes, which can indicate the trend in wet deposition of these compounds. But to assess the total deposition of POPs and Hg it is necessary to consider the reversible exchange between the surface and the atmosphere. This is especially important for assessing deposition to the ocean, an important area of interest for Norway. In Green et al (2011), the air concentrations of POPs combined with meteorological information and estimated exchange rates for various POPs were used to assess det total deposition of POPs to the oceans around Norway.

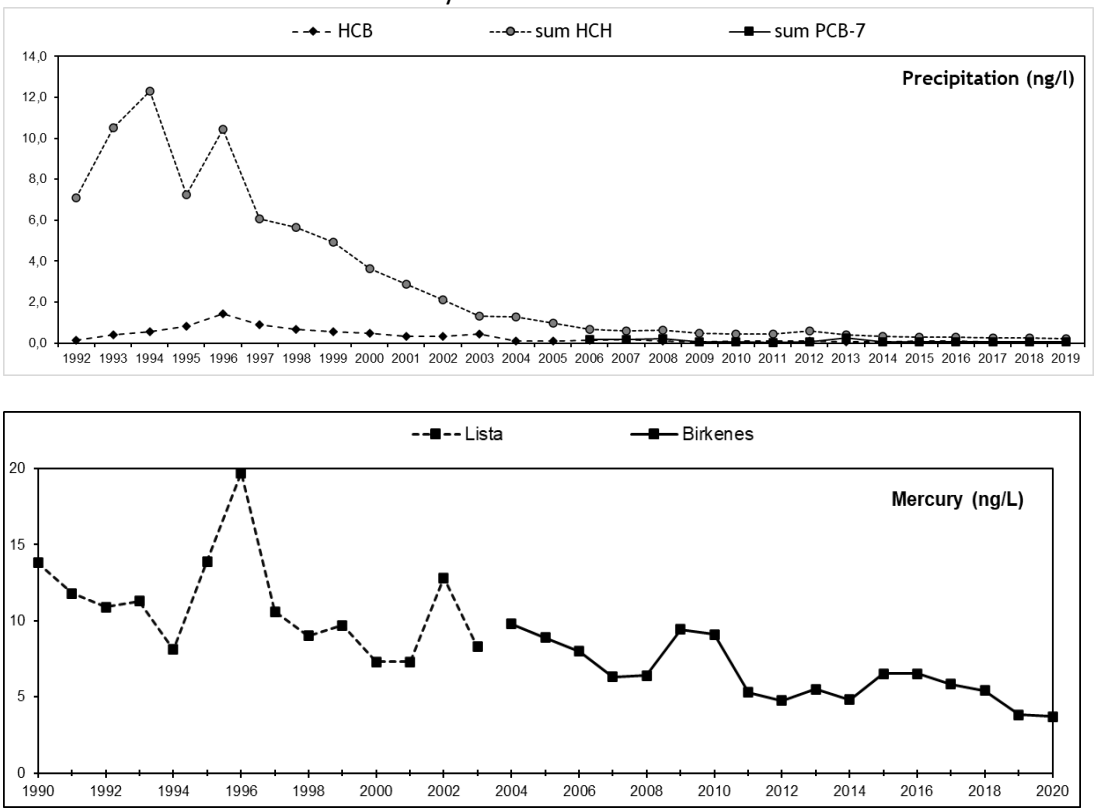


Figure 9: Annual mean concentrations of HCB, sum HCH sum PCB-7 (top) and mercury (bottom) in precipitation at Birkenes (Nizzetto et al., 2021).

2.6 Compliance with international obligations

In EMEP the monitoring strategy (EMEP, 2019) defines the national obligation on what to measure. The monitoring programme is organized in such a way as to enable monitoring stations to operate at three different levels of scope and complexity. Level 1 includes chemical and physical measurements of the basic EMEP parameters (particulate matter, NO_2, ozone, acidifying and eutrophying compounds and heavy metals). It is recommended that the temporal resolution should be daily for most of the observations and at least one to two sites per 100,000 km^2. Norway has the size of 385.000 km^2, thus Ideally, Norway should have seven EMEP sites, but minimum four. Norway has four EMEP sites at the mainland in addition to one at Svalbard, where only the air data are included in EMEP. The four sites contain all the recommended variables at the required temporal resolution, except for PM which is only measured at three sites and with weekly resolution at two of these. The reason for weekly sampling is due to the low concentration of PM at these sites and the difficulty to measure EC/OC at with only 24h sampling, in addition to saving cost.

The Level 2 variables provide a more complete description of the physical/chemical speciation of relevant constituents, which is necessary for assessing air pollution, including long-range transport of air pollutants, and which thus represents an essential supplement to the level 1 activities.

Table 2: Compliance with the EMEP Monitoring strategy (EMEP; 2019) for level 1 sites.

Level 1 - variables to be measured at all basic EMEP sites		Temporal resolution	Norwegian EMEP sites (Table 1)
Inorganic compounds in precipitation	pH, SO_4^{2-}, NO_3^-, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, precipitation amount	24 hours	Birkenes, Hurdal, Tustervatn, Kårvatn
Inorganic compounds in air	SO_2, SO_4^{2-}, NO_3^-, HNO_3, NH_4^+, NH_3, (sNO_3, sNH_4), HCl, Na^+, K^+, Ca^{2+}, Mg^{2+}	24 hours	Birkenes, Hurdal, Tustervatn, Kårvatn, Zeppelin
Elemental and Organic Carbon	EC and OC in $PM_{2.5}$	24 hours / 7 days	Birkenes, Hurdal, Kårvatn
Nitrogen dioxide	NO_2	1 hour/ 24 hours	Birkenes, Hurdal, Kårvatn
Ozone	O_3	1 hour	Birkenes, Hurdal, Tustervatn, Kårvatn, Zeppelin, Prestebakke, Sandve
PM mass concentration	$PM_{2.5}$, PM_{10}	24 hours	Birkenes (24h and 7 days), Hurdal, Kårvatn (7 days)
Heavy metals in precipitation	Cd, Pb, Cu, Zn, As, Cr, Ni	7 days	Birkenes, Hurdal, Kårvatn
Meteorology	amount, temperature, wind, humidity, pressure	1 hour	Birkenes, Hurdal, Zeppelin

Table 3: Compliance with the EMEP Monitoring strategy (EMEP; 2019) for level 2 sites.

Level 2 - to be measured at a subset of sites in addition to level 1		Temporal resolution	Norwegian EMEP sites
VOCs	hydrocarbons (NMHC), aldehydes and ketones (OVOC)	1 hour/grab sample (1-2 pr week)	NMHC at Zeppelin
Nitrogen oxide	NO	1h	-
Methane, Carbon Monoxide	CH_4, CO	1 hour	Zeppelin and Birkenes
PM1		1 hour	-
Elemental and Organic Carbon in air	EC and OC in PM10	1 hour	Birkenes,Hurdal,Kårvatn,Zeppelin
Mineral dust in PM10	Si, Al, Fe, Ca	24hour/7days	Zeppelin and Birkenes (Al and Fe)
Aerosol properties	Absorption, scattering, particle number size distribution, AOD	1 hour	Zeppelin and Birkenes (Stockholm university at Zeppelin)
Particle chemistry speciation	Non-refractory organic and inorganic composition (ACSM, AMS)	1 hour	Zeppelin and Birkenes
Gas particle ratio of N-species	NH_3/NH_4^+, HNO_3/NO_3^- (artefact-free methods)	1 hour/24 hours/1month	-
Mercury in air	Hg (gaseous elemental mercury (GEM)	1 hour	Birkenes,Andøya,Zeppelin
Mercury in precipitation	Hg	24 hours/7 days	Birkenes, Hurdal, Kårvatn
Heavy metals in air	Cd, Pb, Cu, Zn, As, Cr, Ni	7 days	Birkenes,Andøya*,Zeppelin
POPS in air	PAHs, PCBs, HCB, chlordane, HCHs, DDT/DDE	24 hours/7 days	Birkenes,Andøya*,Zeppelin
POPs in precipitation	PAHs, PCBs, HCB, chlordane, HCHs, DDT/DDE	7 days	Birkenes
Halocarbons	CFCs, HCFCs, HFCs, PFCs, SF6	1 hour	Zeppelin

*Andøya will be closed in 2022

For level 2 variables, all Parties with a land area greater than 50,000 km^2 should operate at least one site, but Parties have the possibility to choose and focus on variables reflecting their national priorities if there are obstacles to or financial constraints regarding the implementation of monitoring programmes. In Norway there are two sites defined as EMEP level 2 sites (Table 3). The monitoring programme includes most of the recommended components except oxygenated VOCs, NO, PM_1 and artefact free method for gas particle ratio of N-species.

Level 3 measurements are research-driven and may be partly available at locations other than sites offering level 1 and level 2 data. These observations may address national or European priority pollution issues, it can be campaigns or more long-term commitments. In Norway there are observations of organic tracers, greenhouse gases, POPs, and organic contaminants of emerging concern that can be identified as level 3 components.

The monitoring requirements in CAMP is less demanding than EMEP with respect to both number of components and temporal resolution of the observation. The detailed commitments of Contracting Parties on atmospheric monitoring are set out in the Guidance for CAMP (OSPAR, 2015). CAMP call for each Contracting Party bordering the OSPAR maritime area to operate at least one monitoring station on the coast and/or offshore and where Parties border more than one region at least one station should be operating in each. The stations should be located not more than 10 km from the coastline, but there are exceptions to improve the spatial coverage of the programme. In Norway this means two sites at minimum. Bordering to Region I: Arctic Waters and Region II: Greater North Sea. Andøya, Zeppelin/Ny Ålesund and Kårvatn are belonging to Region I, while Birkenes, Nausta and Vikedal to Region II. The components listed in Table 1, for these sites, comply well with what is required in Table 4.

Table 4: Components to be measured under CAMP.

	Mandatory	Voluntary
Precipitation	Cd, Pb, Hg, Ni NH_4^+, NO_3^-	As, Cr, Cu, Zn PAHs *(For QC: pH, Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-)*
Airborne	NO_2, HNO_3, NH_3, NH_4^+, NO_3^- (a) Cd, Pb, Ni	$Hg_{(g)}$ PCBs

a) total ammonium (NH_3 + NH_4^+) and total nitrate (HNO_3 +NO_3^-) are alternatives

The EU air quality directive (2008/50/EC and 2004/107/EU) includes requirements for observation in regional background. In Table 5, an overview of which of the sites and observations given in Table 1 are reported to EEA.

Table 5: Overview of sites, observations and its data completeness reported to EEA for 2020.

By	Stasjon	Eol-kode	PM10	PM2,5	NO	NO2	NOx	CO	Ozon	Benzen	SO2	As	Cd	Ni	Pb	Hg	B(a)P
Regional industri	Karpdalen	NO0094A									99	99	99	99	99		
	Svanvik	NO0047R									96	81	81	81	81		
Regional bakgrunn	Birkenesobservatoriet	NO0002R	96	90		95			99		96	98	98	98	98	85	14
	Hurdal	NO0056R	98	100		96			99		99						
	Kårvatn	NO0039R	97	37		99			92		100						
	Prestebakke	NO0043R							97								
	Sandve	NO0052R							99								
	Tustervatn	NO0015R				100			100		100						
	Andøya	NO0090R										28	28	28	28	95	
	Zeppelinfjellet	NO0042R							99		96	29	29	29	29	82	29

3 Moss surveys

Since the 1970s, it has been evident that samples of terrestrial mosses may be used for the monitoring of atmospheric deposition of pollutants such as heavy metals. Based on experience from the Nordic countries a network for moss sampling and analysis with respect to key heavy metals, covering a large part of Europe, has been established where coordinated surveys are carried out every five years (Frontasyeva et al. 2020). In Norway nationwide atmospheric deposition surveys for trace metals based on sampling on the terrestrial moss Hylocomium splendens have been conducted at regular intervals since 1977, the last one in 2015 (Steinnes et al., 2015). A linear relation between concentration in moss and wet deposition rate has been well established for several elements (Berg and Steinnes, 1997, Nickel et al. 2018).

The Norwegian moss survey is part of the International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP-Vegetation) under the UNECE LRTAP and includes includes a large part on Europe (Frontasyeva et al. 2020). The survey primarily applies to ten elements that are prioritized in the European programme: Vanadium, chromium, iron, nickel, copper, zinc, arsenic, cadmium, mercury, and lead. In addition, content of 43 other elements in moss are reported.

In the latest survey conducted in 2015, samples of Hylocomium splendens were collected at 230 sites all over mainland Norway. The number of sampling sites were reduced by 50% used in the 1995, 2000, 2005, and 2010 moss surveys. Even so, there is good agreement in the spatial gradient between the datasets, illustrated with deposition maps for lead in Figure 10: . The gradient seen are typical for elements wich mainly origin from emission sources at the European continent Some influence of domestic industries can be seen in some samples such as Cr at Mo i Rana, and Zn at Odda. A specific moss survey around Norwegian industries has been carried out simultaneous with the present national survey.

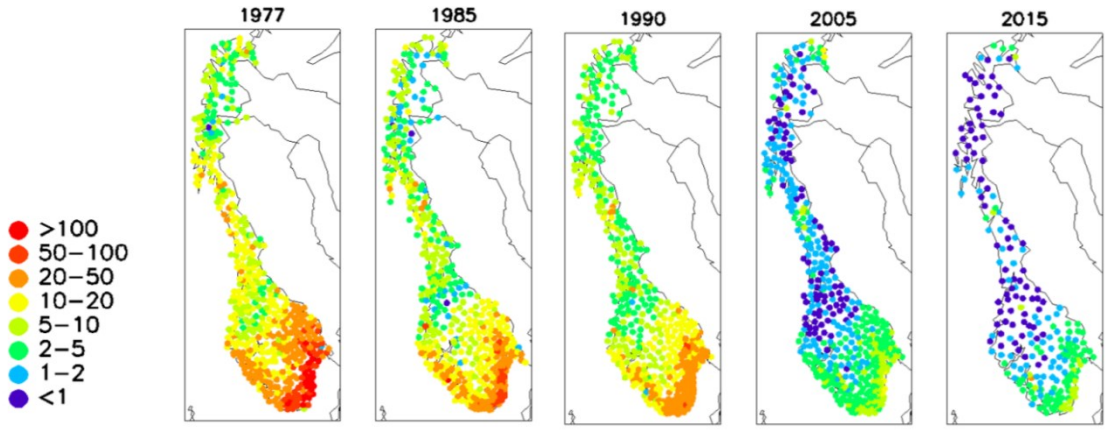
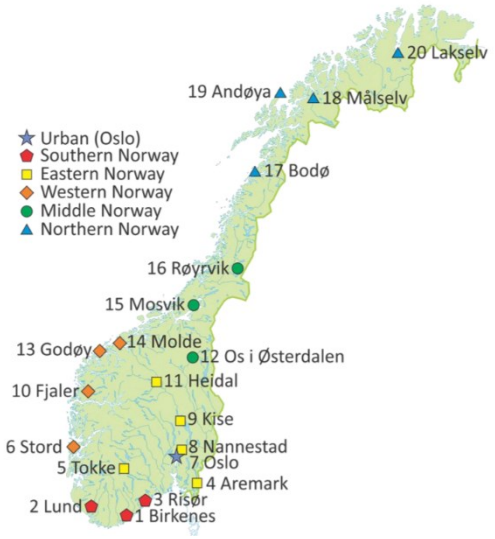


Figure 10: Concentration on lead in moss in Norway (mg kg^{-1}) at five different years in the time period 1977-2015. The colour scheme applies to all maps (Steinnes et al , 2016).

It has also been shown that terrestrial mosses can be useful as biomonitors of some atmospheric POPs and these compounds have therefore been included in the ICP Vegetation Moss Survey (Frontasyeva et al., 2020). In 2010 and 2015 separate moss samples were collected at 20 sites distributed over the country (Schlabach et al. 2016), and the concentrations of several groups of persistent organic pollutants such as polychlorobiphenyl (PCB), polycyclic aromatic hydrocarbon (PAH), and polybrominated diphenyl ether (PBDE) were determined. (Figure 11). The geographical patterns are

influenced by local sources as well as long-range transport, depending on the substance considered. The south to north distribution depends on the volatility of the compounds.

The moss survey provides knowledge about the general temporal and spatial trends of POP contamination in Norway that is difficult to achieve by other means without substantially increased cost.



Parameter	Single compounds	Comment
PCB	PCB-28, -52, -101, -118, -138, -153, -180 (plus -18, -31, -33, -37, -47, -66, -74, -99, -105, -114, -122, -123, -128, -141, -149, -156, -157, -167, -170, -183, -187, -189, -194, -206, -209)	
PBDE	BDE-47, 99, 100, 153, 154, 183, 196, 206 og 209	
PAH	Naphtalene, Acenaphthylene, Acenaphthene, Fluorene, Phenanthrene, Anthracene, Fluoranthene, Pyrene, Benz(a)anthracene, Chrysene, Benzo(b)fluoranthenes, Benzo(k)fluoranthenes, Benzo(a)pyrene, Indeno(1,2,3-cd)pyrene, Dibenzo(ah)anthracene, and Benzo(ghi)perylene.	
Other organochlorine compounds	α-HCH,γ-HCH, HCB, p,p'-DDE, p,p'-DDD, p,p'-DDT, o,p'-DDE, o,p'-DDD, o,p'-DDT	Only p,p'-DDE were regularly detected above LoD[1]
PFC	PFOS, PFOA, PFNA, PFDcA (c10), PFUnA(c11), PFDoA (c12), PFTrA (c13), PFBS og PFHxS	All compounds were below LoD[1]
Other brominated flame retardants	Decabromodiphenyl ethane (DBDPE)	All compounds were below LoD[1]
Chloroparaffins	SCCP (C10-C13) and MCCP (C14-C17)	All compounds were below LoD[1]

Figure 11: Sites and measurement program for the moss survey of POPs in 2015 (Schlabach et al. 2016).

4 Monitoring of aerosol properties, ozone layer, ozone depletion and climate gases.

Monitoring of the atmospheric ozone layer (Total ozone) and natural ultraviolet radiation are measured daily at Kjeller, Andøya and in Ny-Ålesund (Figure 1). These ground-based observations are combined with satellite measurements to assess the development of the ozone layer. Annual observation trend assessment and information of method are reported by Svendby et al (2021)

The monitoring programme greenhouse gases and particle physical and optical properties are performed at two sites, Birkenes and Zeppelin (Figure 1). The atmospheric monitoring programme include the measurements of totally 46 climate gases, whereof several also have strong ozone depleting effects, and it includes observations of relevant optical and physical properties of aerosols. Annual observation, trend assessment and information of method are reported by Myhre et al (2021).

5 Monitoring in urban environment

The urban observations include traffic sites as well as urban background and more residential type of sites. The requirement for monitoring is given by the EU directive (EU 2002 and 2008). These requirements are also included also in Norwegian law.

In 2020, there were in total 78 air quality sites in Norway representing 28 different cities or urban environment which was reported to EEA as well as to national authorities (Figure 1 and Table 6). The measurement program mainly consists of PM_{10}, $PM_{2.5}$ and NO_2, but some includes CO, O_3, SO_2, benzene, PAH or heavy metals depending on the priorities in the specific region. It should be noted that these observations are primarily used for air quality purposes and not used for estimating atmospheric deposition.

Table 6: Norwegian urban sites and components reported to EEA. Colour codes indicate to type of instrumentation: green: automatic, orange: active sampling, yellow: passive sampling.

City	Name	Station type	PM_{10}	$PM_{2.5}$	NO_2	CO	O_3	SO_2	C_6H_6	BaP	As,Cd,Ni
Bergen	Danmarks plass	traffic	x	x	x						
	Klosterhaugen	background	x	x	x		x				
	Loddefjord	traffic	x	x	x						
	Rådal	traffic	x	x	x						
	Rolland, Åsane	background	x	x	x						
Bodø	Olav V gate	traffic	x	x							
Brumunddal	Ringsakervegen	traffic	x	x							
Bærum	Bærum Golfklubb	near city background					x				
	Bekkestua	traffic	x	x	x						
	E18 Høvik kirke	traffic	x	x	x						
Drammen	Backeparken	background	x	x							
	Bangeløkka	traffic	x		x				x		
	Vårveien	traffic	x	x							
Elverum	Leiret	traffic	x	x	x						
Fredrikstad	Nygaardsgata	background	x	x	x						
	St.Croix	traffic	x	x	x						
Gjøvik	Minnesundvegen, Gjøvik	traffic	x	x	x						
Grenland	Furulund	industry	x	x	x			x			
	Haukenes	near city background			x		x				
	Knarrdalstranda	background	x	x	x						
	Lensmannsdalen	traffic	x	x	x				x		
	Sverresgate	traffic	x		x						
Hamar	Vangsveien, Hamar	traffic	x	x	x						
Harstad	Seljestad Rv83	traffic	x	x							
Kristiansand	Bjørndalssletta	traffic	x	x	x				x		
	Hennig Olsen	industry									x
	Konsul Wilds vei	industry						x			
	Stener Heyerdahl	background	x	x	x				x		
Levanger	Kirkegata	traffic	x	x							
Lillehammer	Bankplassen	traffic	x	x	x				x		
	Lillehammer barnehage	background	x	x	x					x	
Lillesand	Holta	industry						x			
	Holta øst	industry								x	
Lillestrøm	Vigernes	traffic	x	x	x						
	Vollaparken øst	background									
Lørenskog	Solheim	traffic	x	x	x						
Mo i Rana	Moheia Vest	industry	x	x							
Moss	Kransen	traffic	x	x							
Narvik	Sentrum	traffic	x	x							
Oslo	Alnabru	traffic	x	x	x						
	Bryn skole	background	x	x	x						
	Bygdøy Alle	traffic	x	x	x						
	E6 Alna senter	traffic	x	x	x						
	Hjortnes	traffic	x	x	x					x	
	Kirkeveien	traffic	x	x	x	x			x		
	Loallmenningen	background	x	x	x						
	Manglerud	traffic	x	x	x						
	Rv 4, Aker sykehus	traffic	x	x	x						
	Skøyen	background	x	x							
	Smestad	traffic	x	x	x				x		
	Sofienbergparken	background	x	x	x		x	x		x	
	Spikersuppa	background	x	x							
	Vahl skole	traffic	x	x							
Sarpsborg	Alvim	traffic	x	x							
	Vollgata	industry						x			
	Kannik	traffic	x	x	x						
	Schancheholen	traffic	x	x	x						
	Vågen	background									
	Våland	background	x	x	x						
Sør-Varanger	Karpdalen	industry						x			x
	Svanvik	industry						x			x
Tromsø	Hansjordnesbukta	traffic	x	x	x						
	Rambergan	background	x								
Trondheim	Åsveien skole	traffic	x	x	x						
	E6-Tiller	traffic	x	x	x						
	Elgeseter	traffic	x	x	x				x		
	Omkjøringsvegen	traffic	x	x	x						
	Torvet	background	x	x	x					x	
Tønsberg	Nedre Langgate	traffic	x	x	x						
Ålesund	Grimmerhaugen	background	x								
	Karl Eriksens plass	traffic	x		x				x		

From 2022, the Norwegian monitoring programme for environmental contaminants will initiate monitoring of organic contaminants of emerging concern and heavy metals including Hg in air at one urban site in Oslo (Table 7). The site is chosen to represent an urban background area without direct input of local emissions. For this, Sofienbergparken has been selected. Sampling will be performed using the same active sampling methodologies as at the established background sites. Samples for each compound class will be collected on monthly basis, 48 hrs per sample. The purpose of the urban measurements is to establish an early warning tool for emerging contaminants but also to put the results from the background sites in comparison to a source site.

Table 7: Sampling strategy at the Norwegian Urban observatory for organic contaminants and heavy metals.

Compound class	Air sampling methodology
Heavy metals (Pb, CD, Zn, Cu, Cr, Co, Mn, Ni, V, As, Ag)	Digitel High-volume Active air sampler
Hg	Tekran
PFAS (n=53)	Digitel High-volume Active air sampler
SCCP, MCCP, Dechloranes (n=7), Chlorinated flame retardants (n=4)	Digitel High-volume Active air sampler
PBDE (n=22), HBCD (n=3), nBFR (n=10)	Digitel High-volume Active air sampler
OPFRs (n=17), plasticizers (n=7)	Digitel High-volume Active air sampler
PCP+PCA (n=2), UV-compounds (n=10)	Digitel High-volume Active air sampler
Siloxanes (n=10)	ABN-sampler
nBFR	ABN-sampler
Hexachlorobutadiene	ABN-sampler

6 Final remarks

The Norwegian monitoring programmes have had (and still has) a long-term perspective, which has made the observations valuable far beyond national interests. The commitment to international programmes has been extremely important to develop standardised methodology and share knowledge on atmospheric composition and deposition. The policy of open data sharing has been a prerequisite.

In addition to the long-term perspectives, the close connection between the research and regulatory sector in Norway allows for a continuous renewal of the monitoring programme. I.e., lifting contaminants from screening/novel level to monitoring level allows for fast development of standardized methods and the data give important inputs to regulators.

The different programmes benefit from being organised together. Sharing infrastructures (observatories, laboratory, and database) is cost efficient and creates synergies across environmental topics. To understand the effect as well as sources of air pollution and deposition, a wide range of components needs to be measured and collocated.

When considering atmospheric deposition, it is a challenge having sufficient representative number of sites, especially difficult in Norway with large geographical differences. In addition, it is a challenge to estimate the representative dry deposition velocities without site specific flux measurements. It is especially difficult for POPs and Hg where the reversible exchange with surface is important. To get further insight and improved estimate of deposition there are interesting development in various measurement model fusion tools which may become part of more routine monitoring products in the future.

7 References

Aas, W., Hjellbrekke, A-G., Fagerli, H. and Benedictow, A.: Deposition of major inorganic compounds in Norway 2012–2016. NILU OR 41/2021. Kjeller, NILU, http://hdl.handle.net/11250/2485535, 2017

Aas, W. and Nizzetto, P. B.: Heavy metals and POP measurements 2019. EMEP/CCC-Report 3/2021, Kjeller, NILU, https://projects.nilu.no/ccc/reports.html, 2021.

Aas, W., Fiebig, M., Solberg, S., and Yttri, K. E.: Monitoring of long-range transported air pollutants in Norway. Annual Report 2020. NILU report 13/2021; M-2072|2021, Kjeller, NILU, https://hdl.handle.net/11250/2767251, 2021

Berg, T. and Steinnes, E.: Use of mosses (Hylocomium splendens and Pleurozium Schreberi) as biomonitors of heavy metal deposition: From relative to absolute values. Environ. Pollut., 98, 61-71, 1997.

Berglen, T.F., Nilsen, A.-C., Våler, R.L., Vadset, M., Uggerud, H. T., Hak, C., Andresen, E.: Grenseområdene Norge - Russland. Luft- og nedbørkvalitet 2020. Kjeller, NILU (MD report, M-1957|2021) (NILU report, 06/2021). Kjeller, NILU, https://hdl.handle.net/11250/2761749, 2021

EMEP: Monitoring strategy for the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe for the period 2020-2029, ECE/EB.AIR/144/Add.1, https://unece.org/fileadmin/DAM/env/documents/2019/AIR/EB_Decisions/Decision_2019_1.pdf, 2019

EU (2002) Directive 2002/3/EC of the European Parliament and of the Council of 12 February 2002 relation to ozone in ambient air. *Off. J. Eur. Com.,* L 067, 09/03/2002, 14-30.

EU (2008) Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. *Off. J. Eur. Com.,* L 141, 11/06/2008, 1-44.

Frontasyeva M., Harmens H., Uzhinskiy A., Chaligava, O. and participants of the moss survey: Mosses as biomonitors of air pollution: 2015/2016 survey on heavy metals, nitrogen and POPs in Europe and beyond. Report of the ICP Vegetation Moss Survey Coordination Centre, Joint Institute for Nuclear Research, Dubna, Russian Federation, https://icpvegetation.ceh.ac.uk/sites/default/files/REPORT-Frontasyeva.pdf, 2020

Green, N.W., Heldal, H.E., Måge, A., Aas, W., Gäfvert, T., Schrum, C., Boitsov, S., Breivik, K., Iosjpe, M. Yakushev, E., Skogen, M., Høgåsen, T., Eckhardt, S., Christiansen, A.B., Daae, K.L., Durand, D., Debloskaya, E. (2011) Tilførselsprogrammet 2010. Overvåking av tilførsler og miljøtilstand i Nordsjøen. Oslo, NIVA (Statlig program for forurensingsovervåking. Rapport 1097/2011. TA-2810/2011) (NIVA-rapport 6187 2011) (In Norwegian).

Mills, G., Pleijel, H., Braun, S., Büker, P., Bermejo, V., Calvo, E., Danielsson, H., Emberson, L., González Fernández, I., Grünhage L., Harmens, H., Hayes, F., Karlsson, P.-E., Simpson, D.: New stomatal flux-based critical levels for ozone effects on vegetation. Atmos. Environ., 45, 5064-5068, 2011.

Myhre, C.L., Svendby, T., Hermansen, O., Lunder, C., Platt, S.M., Fiebig, M., Fjæraa, A.M., Hansen, G., Schmidbauer, N. and Krognes, T.: Monitoring of greenhouse gases and aerosols at Svalbard and Birkenes in 2020. (NILU report 22/2021). Kjeller, NILU, https://hdl.handle.net/11250/2832204, 2021

Nickel, S., Schröder, W., Schmalfuss, R., Saathoff, M., Harmens, H., Mills, G., Frontasyeva, M. V., Barandovski, L., Blum, O., Carballeira, A., de Temmerman, L., Dunaev, A. M., Ene, A., Fagerli, H., Godzik, B., Ilyin, I., Jonkers, S., Jeran, Z., Lazo, P., Leblond, S., Liiv, S., Mankovska, B., Núñez-Olivera, E., Piispanen, J., Poikolainen, J., Popescu, I. V., Qarri, F., Santamaria, J. M., Schaap, M., Skudnik, M., Špirić, Z., Stafilov, T., Steinnes, E., Stihi, C., Suchara, I., Uggerud, H. T., and Zechmeister, H. G..:

Modelling spatial patterns of correlations between concentrations of heavy metals in mosses and atmospheric deposition in 2010 across Europe. Environ. Sci. Eur., 30, 53, https://doi.org/10.1186/s12302-018-0183-8, 2018

Nizzetto, P.B., Aas, W., Halvorsen, H.L., Nikiforov, V., Pfaffhuber, K.A.: Monitoring of environmental contaminants in air and precipitation. Annual report 2020. (MD report M-2060|2021) (NILU report, 12/2021), Kjeller, NILU, https://hdl.handle.net/11250/2778509, 2021

OECD: The OECD Programme on Long Range Transport of Air Pollutants. Measurements and Findings. Organisation for Economic Co-operation and Development, Paris 1977, https://projects.nilu.no/ccc/reports/paris_1977.pdf, 1977

OSPAR: Guidance for the Comprehensive Atmospheric Monitoring Programme (CAMP), Agreement 2015-04, https://www.ospar.org/documents?d=33045, 2015.

Schlabach, M., Steinnes, E., Uggerud, H.T. Atmospheric deposition of organic contaminants in Norway: National moss survey 2015. NILU report 30/2016. Kjeller, NILU, http://hdl.handle.net/11250/2428266, 2016

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L. D., Fagerli, H., Flechard, C. R., Hayman, G. D., Gauss, M., Jonson, J. E., Jenkin, M. E., Nýiri, A., Richter, C., Semeena, V. S., Tsyro, S., Tuovinen, J.-P., Valdebenito, A., Wind, P.: The EMEP MSC-W chemical transport model – technical description. Atmos. Chem. Phys., 12, 7825–7865, doi:10.5194/acp-12-7825-2012, 2012

Steinnes, E., Uggerud, H. T., Pfaffhuber, K. A., Berg, T.: Atmospheric deposition of heavy metals in Norway. National moss survey 2015. NILU report 28/2016. Kjeller, NILU, http://hdl.handle.net/11250/2435217, 2016

Svendby, T.M., Hansen, G.H., Bäcklund, A., Nilsen A.-C., Schulze, D., Johnsen. B.: Monitoring of the atmospheric ozone layer and natural ultraviolet radiation. Annual report 2020. (NILU report, 18/2021), Kjeller, NILU, https://hdl.handle.net/11250/2779129, 2021

Timmermann, T., Andreassen, K., Beachell, A. M., Brurberg, M. B., Børja, I., Clarke, N., Halvorsen, R., Hylen, G., Jepsen, J. U., Perminow, J. I. S., Solberg, S., Solheim, H., Talgø, V., Tollefsrud, M. M., Vindstad, O. P. L., Økland, B., Økland, T., Aas, W.: Skogens helsetilstand i Norge. Resultater fra skogskadeovervåkingen i 2019, NIBIO rapport, 6(119), Ås, NIBIO, https://hdl.handle.net/11250/2681543, 2020

Tørseth, K., Aas, W., Breivik, K., Fjæraa, A. M., Fiebig, M., Hjellbrekke, A. G., Lund Myhre, C., Solberg, S., and Yttri, K. E.: Introduction to the European Monitoring and Evaluation Programme (EMEP) and observed atmospheric composition change during 1972–2009, Atmos. Chem. Phys., 12, 5447–5481, https://doi.org/10.5194/acp-12-5447-2012, 2012

UN/ECE: The 1999 Gothenburg Protocol to the 1979 convention on long-range transboundary air pollution to abate acidification, eutrophication and ground-level ozone. **URL:** http://www.unece.org/env/lrtap/multi_h1.html, 1999

Yttri, K. E., Canonaco, F., Eckhardt, S., Evangeliou, N., Fiebig, M., Gundersen, H., Hjellbrekke, A.-G., Lund Myhre, C., Platt, S. M., Prévôt, A. S. H., Simpson, D., Solberg, S., Surratt, J., Tørseth, K., Uggerud, H., Vadset, M., Wan, X., and Aas, W.: Trends, composition, and sources of carbonaceous aerosol at the Birkenes Observatory, northern Europe, 2001–2018, Atmos. Chem. Phys., 21, 7149–7170, https://doi.org/10.5194/acp-21-7149-2021, 2021.

NILU – Norwegian Institute for Air Research

NILU – Norwegian Institute for Air Research is an independent, non-profit institution established in 1969. Through its research NILU increases the understanding of climate change, of the composition of the atmosphere, of air quality and of hazardous substances. Based on its research, NILU markets integrated services and products within analysing, monitoring and consulting. NILU is concerned with increasing public awareness about climate change and environmental pollution.

NILU's values: *Integrity - Competence - Benefit to society*
NILU's vision: *Research for a clean atmosphere*

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

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

ISBN: 978-82-425-3076-9
ISSN: 2464-3327

Norsk institutt for luftforskning
Norwegian Institute for Air Research