Annual Scientific Report 2021 ------- Official -------

Long-Term Air Quality Monitoring Program
UNESCO World Natural Heritage "Geiranger Fjord", Norway

Jörg Löffler (University of Bonn, Germany)

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Abstract

According to the World Health Organization (2013), air pollution especially by traffic-related particulate matter (PM) is a widespread problem. The health effects of the finer fractions of PM, especially dust particles < 10 µm (PM_{10}) and very fine particles smaller than 2.5 µm ($PM_{2.5}$) are well documented, and there is no evidence of a safe level of exposure or a threshold below which no adverse health effects occur. Even at relatively low concentrations the burden of air pollution on health is significant. Noise is the second-worse environmental cause of ill health (WHO 2011), which is brought along with human activities (especially traffic) and technical infrastructure. Furthermore, NOx and SO_2 are of major health importance.

The air quality monitoring program focuses on investigating the sources, the quantities, the mechanisms of spatio-temporal distribution of PM and accompanying gaseous pollutants, and their climatic driving forces in a long-term perspective. In 2017, the program was extended, also monitoring sound level (dbC); we further extended sound level measurements in 2019, now also covering dbA, which was requested to better address the legal limits for sound levels. Our continuous gas measurements are challenging as permanent GSM net coverage is required (on not permanently guaranteed in the mountains), and equipment is sensitive under the specific weather conditions in the fjord.

We here report on the results from 1st September 2020 until 31st August 2021.

From a scientific perspective, this second *Corona* year again offered kinds of laboratory conditions, with very limited sea traffic during the peak summer season, and an onset of cruise ship activities in August 2021. Our previous hypotheses on the pollution patterns could thus be tested under more or less controlled conditions. As a result, the situation is complex. Interpretation of the data should be done with caution. Over-simplification might lead to wrong conclusions.

Since the last report in 2020, our understanding of the mechanisms behind the observed patterns of air pollution has further developed. Radiation determined thermal air convection, persistence and altitude of inversion layers as well as cold air streams serve as the main drivers for the spatial distribution of pollutants in specific topography. Momentary pollution patterns are situation dependent.

This sixth report delivers a unique set of examples of how air quality develops under certain conditions. Cumulative effects of pollutants (not only particles) in the short-term (hours and days) and in the long-term (weeks and months) are the major challenge. Even single emitting events might largely contribute to long-lasting poor air quality.

Different types of emissions are involved, e.g. combustion of heavy oil (raw diesel) in ship motors, combustion of diesel in road vehicles, burning firewood for winter heating, and larger waste-burn events. We here again show, that the major issue are ultra-fine particle concentrations which are, once exposed to the valley atmosphere, trapped in the complex topography, where decontamination of the entire air volume in the narrow valley is limited.

We conclude that the situation is complex. Pollution can be temporarily high, even if the total amount of emissions is limited.

1. Introduction

Air pollution especially by dust is estimated to cause deaths directly, and it has been shown how the adverse effects of ultrafine air particles are linked to their ability to gain access to the lung and systemic circulation, where toxic components lead to tissue damage and inflammation (Nel 2005). It has since been an intense debate at political levels worldwide to limit the amount of air pollutants brought to the human environment in order to help to prevent mortality by particulate matter (e.g. WHO 2013). Furthermore, NOx and SO_2 are of major health importance (e.g. Kurtenbach et al. 2016).

Nel, A. (2005): Air Pollution-Related Illness: Effects of Particles. Science 308: 804-806. DOI: 10.1126/science.1108752

World Health Organization (WHO) (2013): Health Effects of Particulate Matter. WHO Regional Office for Europe. Copenhagen.

Kurtenbach et al. (2016): Emissions of NO, NO_2 and PM from inland shipping. Atmospheric Chem. Phys. 16: 14285-14295.

Our air quality monitoring program in the Geiranger area focuses on investigating the sources, the quantities, the mechanisms of spatio-temporal distribution, and their climatic driving forces in a long-term perspective. The program follows a low budget approach, and is based on high-tech infrastructure and measurement techniques. We here test new ideas and hypotheses, and as such the research program does not always follow standard protocols and technical norms. There are drawbacks, e.g. when it comes to permanent measurements mainly based on battery power supply. As such, the setup of the gradient based spatially organized project infrastructure is also a research project itself. As a consequence, the data set consists of periods with missing data which often does not yet allow to present averaged data which contribute to the assessment based on legal limits (i.e. annual means).

This new report presents results from 1st September 2020 until 31st August 2021.

From a scientific perspective, this *Corona* year offered kinds of laboratory conditions, with limited sea traffic. Our previous hypotheses on the pollution patterns could thus be tested under more or less controlled conditions.

The aim of this report is to inform about the air quality situation in the area and help to understand the driving forces and physical mechanisms behind pollution patterns. Explicitly, the report DOES NOT deliver any solutions or suggestions for potential political consequences.

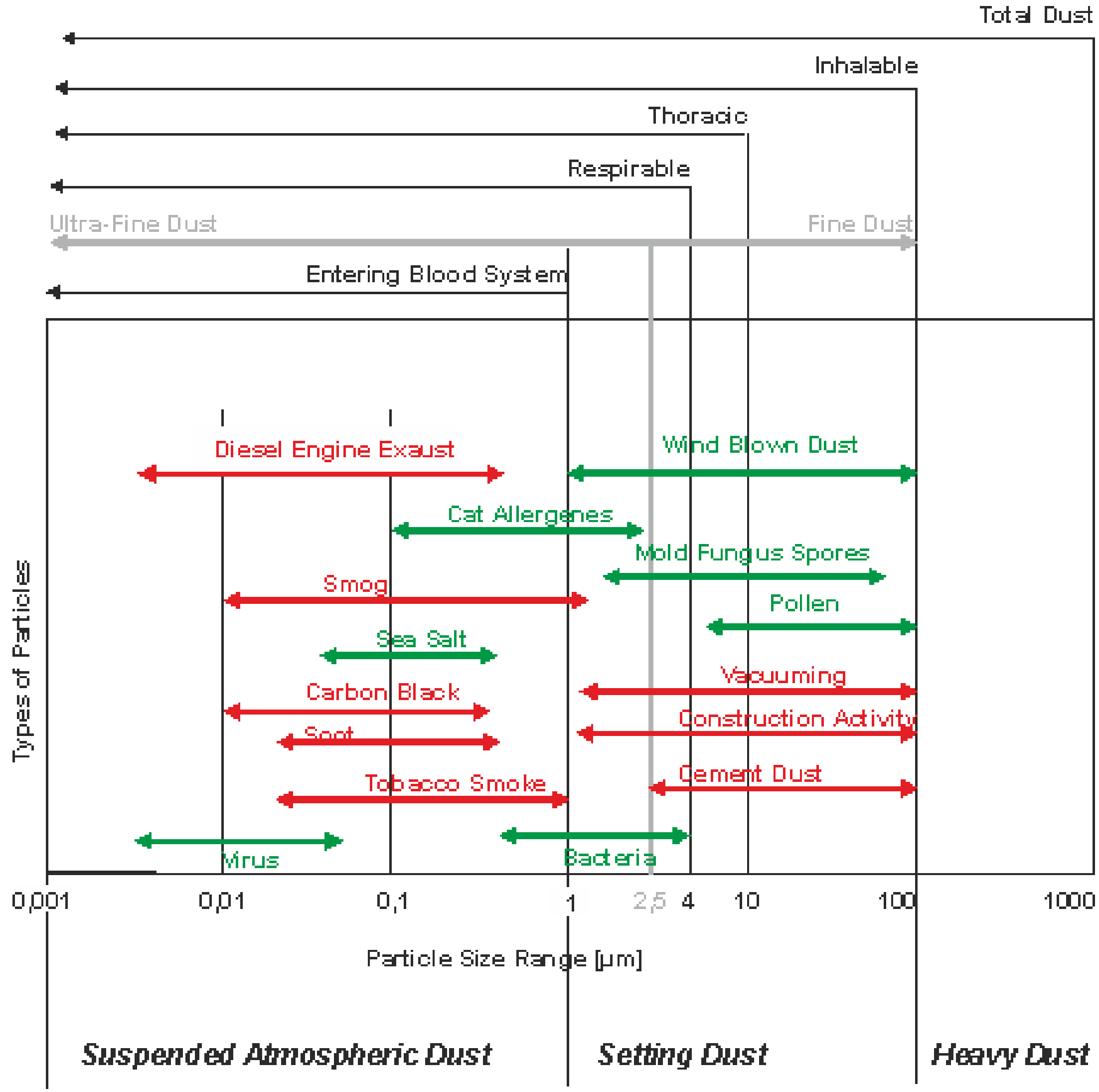
1.1 Air Quality Variables (Matter)

Particulate Matter (PM) is a measure of dust particles with an aerodynamic diameter of smaller than x micrometers [µm].

We used the following PMx fractions: PM_{total}, PM_{10}, PM_4, $PM_{2.5}$, and PM_1 which allow to roughly detect their potential origin, and which are important measures concerning the impact of dust on human health.

Whereas e.g. PM_{10} includes all particles <10µm, "PM10-total" is used to amount for the concentration of a certain fraction: PM10-total, PM4-10, PM2.5-4, and PM2.5-1.

Some particulates occur naturally. Human activities such as burning of fossil fuels in vehicles or coal combustion also generate significant amounts of particulates.



1.2 Air Quality Variables (Gases)

Oxides of Nitrogen (NOx) composed of two species of oxides of nitrogen nitric oxide (NO) and nitrogen dioxide (NO_2). Annual mean concentrations of NO_2 in urban areas are generally in the range 20-90 µg/m³. Levels vary significantly throughout the day, with peaks occurring during rush hour traffic. Maximum daily and one hourly means can be as high as 400 µg/m³ and 1200 µg/m³ respectively. Globally, NOx quantities produced naturally by bacterial and volcanic action or lightning far outweigh man-made emissions. Anthropogenic emissions are mainly due to fossil fuel combustion.

Sulphur Dioxide (SO_2) is a colorless gas which reacts on the surface of a variety of airborne solid particles, is soluble in water, and can be oxidized within airborne water droplets. Annual mean concentrations in major cities are nowadays below 100 µg/m3 with typical mean values in the range of 15-50 µg/m³. Hourly peak values can be 1000-2000 µg/m³. Natural background is about 5 µg/m³. An important sources of SO_2 is fossil fuel combustion. Coal burning is the single largest man-made source of SO_2 accounting for about 50% of annual global emissions, with oil burning accounting for a further 25-30%.

Source: http://www.air-quality.org.uk

1.3 Norwegian Limit Values for Outdoor Air Quality

pursuant to the Regulations relating to pollution control (Pollution Regulations) section 7-6*

Component	Averaging period	Limit value	Margin of tolerance
Sulphur dioxide (SO_2)			
1. Hourly limit value for the protection of human health	1 hour	**350 µg/m³**	The limit value must not be exceeded more than 24 times a calendar year
2. Daily limit value for the protection of human health	1 day (fixed)	**125 µg/m³**	The limit value must not be exceeded more than 3 times a calendar year
3. Limit value for the protection of the ecosystem	Calendar year and winter (1/10-31/3)	**20 µg/m³**	
Nitrogen dioxide (NO_2) and nitrogen oxides (NOx)			
1. Hourly limit value for the protection of human health	1 hour	**200 µg/m³ $N0_2$**	The limit value must not be exceeded more than 18 times a calendar year
2. Annual limit value for the protection of human health	Calendar year	**40 µg/m³ $N0_2$**	
3. Limit value for the protection of vegetation	Calendar year	**30 µg/m³ N0x**	
Particulate matter PM_{10}			
1. Daily limit value for the protection of human health	1 day (fixed)	**50 µg/m³**	The limit value must not be exceeded more than 30 times a calendar year
2. Annual limit value for the protection of human health	Calendar year	**25 µg/m³**	
Particulate matter $PM_{2.5}$			
Annual limit value for the protection of human health	Calendar year	**15 µg/m³**	

* The Ministry of Climate and Environment (2004): Forskrift om begrensning av forurensning (forurensningsforskriften) FOR 2004-06-01. http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20040601-0931.html#map040 (03.10.2017).

1.4 Air Quality Criteria **(NPHI & NEA 2013)**

The Norwegian Institute of Health has drawn up a set of air quality criteria, which have been set *"so low that most people can be exposed to these levels without experiencing harmful effects on health"*. The work is based on a review of literature on current air pollutant and harmful health effects. Research on air pollution and health has found health damage at levels lower than the current limit values for certain components, and is the background for why the air quality criteria have been set relatively low. (Weggeberg et al. 2017)

Component	Averaging period	Air quality criteria
CO	15 min	80000 µg/m³
	Hour	25000 µg/m³
	8 hours	10000 µg/m³
NO_2	15 min	300 µg/m³
	Hour	100 µg/m³
	Year	40 µg/m³
Ozone	Hour	100 µg/m³
	8 hours	80 µg/m³
SO_2	15 min	300 µg/m³
	Day	20 µg/m³
PM10	Day	30 µg/m³
	Year	20 µg/m³
PM2.5	Day	15 µg/m³
	Year	8 µg/m³

NPHI (Norwegian Public Health Institute) & NEA (Norwegian Environment Agency) (2013), "Luftkvalitetskriterier - Virkninger av luftforurensning på helse Rapport 2013: 9. Oslo.

Weggeberg, H., Stenersen, D., Keskitalo, T., Järvinen, E., Sturtz, T.M., Polley, D.A. & Brashers, B. (2017): Emissions to Air and Discharge to Sea from Ships in Fjord Areas with heavy Cruise Traffic. Mapping and proposed Measures. https://www.sjofartsdir.no/globalassets/sjofartsdirektoratet/regelverk-og-int.-arbeid---dokumenter/pollution-from-shipping-in-world-heritage-fjords/ramboll---emissions-to-air-anddischarge-to-sea-from-ships-in-fjord-areas-with-heavy-cruise-traffic.pdf (26.08.2017).

1.5 Noise as an Environmental Quality Variable

"Noise pollution is a growing problem for Europe's environment. Transport and industry are the main sources of concern and long term exposure can damage human health and adversely affect ecosystems. European legislation aims to reduce noise pollution and also highlights the need to preserve areas that are currently unaffected." **EEA (2014)**

Sounds are an essential ingredient of human life. They are meaningful, and provide information about our surroundings. The atmosphere is in constant movement, generating all kinds of sound itself and in its streaming around objects. Harmful sounds are those that negatively affect human health; they include annoyance and sleep disturbance. Communication in all its subtle (orientation, signals of impending danger) or direct (speech, warning signals) forms will disturbed by noise; processes like thinking, reading, writing, sleeping and learning are also disturbed by noise. (EEA (2014)

According to the WHO (2011) noise is the second-worse environmental cause of ill health, behind air pollution only through particulate matter ($PM_{2.5}$).

"Both air and noise pollution associated with motor vehicle traffic have been associated with cardiovascular disease. Similarities in pollution source and health outcome mean that there is potential for noise to confound studies of air pollution and cardiovascular disease, and vice versa, or for more complex interactions to occur." **(Davies et al. 2009)**

EEA (European Environmental Agency) (2014): Good practice guide on quiet areas. Technical Report 04, Copenhagen. https://www.eea.europa.eu/publications/good-practice-guide-on-quiet-areas (04.10.2017).

Davies, H., Vlaanderen, J., Henderson, S. & M. Brauer (2009): Correlation between co-exposure to noise and air pollution from traffic sources. Occupational and Environmental Medicine 66: 347-350.

WHO (World Health Organization) (2011): Burden of Disease from Environmental Noise: Quantification of Healthy Life Years Lost in Europe, WHO Regional Office for Europe, Copenhagen.
http://www.who.int/entity/quantifying_ehimpacts/publications/e94888.pdf?ua=1 (28.08.2017).

1.5.1 Effects of Different Levels of Night Noise on the Population's Health (WHO 2009)

Average night noise level over a year $L_{night, outside}$	Health effects observed in the population
up to 30 db	Although individual sensitivities and circumstances may differ, it appears that up to this level no substantial biological effects are observed. $L_{night, outside}$ of 30 db is equivalent to the no observed effect level (NOEL) for night noise.
30 to 40 db	A number of effects on sleep are observed from this range: body movements, awakening, self-reported sleep disturbance, arousals. The intensity of the effect depends on the nature of the source and the number of events. Vulnerable groups (for example children, the chronically ill and the elderly) are more susceptible. However, even in the worst cases the effects seem modest. $L_{night, outside}$ of 40 db is equivalent to the lowest observed adverse effect level (LOAEL) for night noise.
40 to 55 db	Adverse health effects are observed among the exposed population. Many people have to adapt their lives to cope with the noise at night. Vulnerable groups are more severely affected.
above 55 db	The situation is considered increasingly dangerous for public health. Adverse health effects occur frequently, a sizeable proportion of the population is highly annoyed and sleep-disturbed. There is evidence that the risk of cardio-vascular disease increases.

WHO (World Health Organization) (2009): Night noise guidelines for Europe: WHO Regional Office for Europe. http://www.euro.who.int/__data/assets/pdf_file/0017/43316/E92845.pdf?ua=1 (04.10.2017)

1.5.2 Norwegian Noise Limits

According to Statens Vegvesen (2014) noise is a large environmental problem in Norway; one of those that affects the largest number of people. About 1.3 million people are exposed to road traffic noise levels exceeding 55 dbA outside their homes. Indoor noise levels shall not exceed a 24 hours average level of 42 dbA. The EU directive 2002/49/EC Assessment and management of environmental noise is implemented in our legal framework as a part of a regulation to the Pollution Control Act.

https://www.vegvesen.no/en/professional/Environment/Noise

1.5.3 International Standard for Allowable Exposure Durations (per IEC 60804) **(WHO 2017)**

Duration per Day (Hours)	Sound Level, dbA
24	80
16	82
8	85
4	88
2	91
1	94

WHO (World Health Organization) (2017): Occupational exposure to noise: evaluation, prevention and control. http://www.who.int/occupational_health/publications/occupnoise/en/ (04.10.2017)

2. Methods and Materials

We permanently measured air quality variables at different locations, Geiranger Fjord (G) ~1 m a.s.l., Fjord Centre (C) ~90 m a.s.l., and Dalen (D) ~450 m a.s.l. Particulate matter (PM) had different fractions, which were detected as µg/m^3 air volume with a *Dusttrak DRX 8534* (TSI) 10-minute samplings from 5-sec. data were averaged as hourly data. Gaseous variables (also measured at 770 m a.s.l., since 2020) were CO, NO, NO_2, and SO_2. Ozone was also measured, but there were inconsistencies among the stations and sensors, so that we decided not to integrate ozone in this report. Data from 10-minute sampling intervals were stored as hourly data from each two parallel *AQMesh* pods. Sound levels were recorded using two separate *testo t816-1* sound level meters, for dbC and dbA, at Fjord level using 1-minute recordings from 1-second measurements.

Our explanatory variables were measured as 1-minute raw data stored as hourly data by our weather station at the Fjord shore: Air pressure, air temperature, air humidity, global radiation, precipitation, wind direction, and wind speed were recorded using a *ADL-MX* logger and high precision standard sensors.

Please note that all time stamps are GMT+1.

Data were quality checked and thereafter aggregated to daily sums or averages, respectively. Most of the graphs in this report are based on daily data. In some specific hourly data were used (explicitly mentioned).

This is a low budget long-term monitoring program. Absolute air quality values were NOT calibrated in the field with high-precision equipment. *AQMesh* sensors were calibrated using one base sensor (at Fjord level) and all others as so called “rovers”, making sure that all sensors were relatively calibrated. *Dusttrak* equipment was calibration at the TSI labs, after 6 months run-time, each.

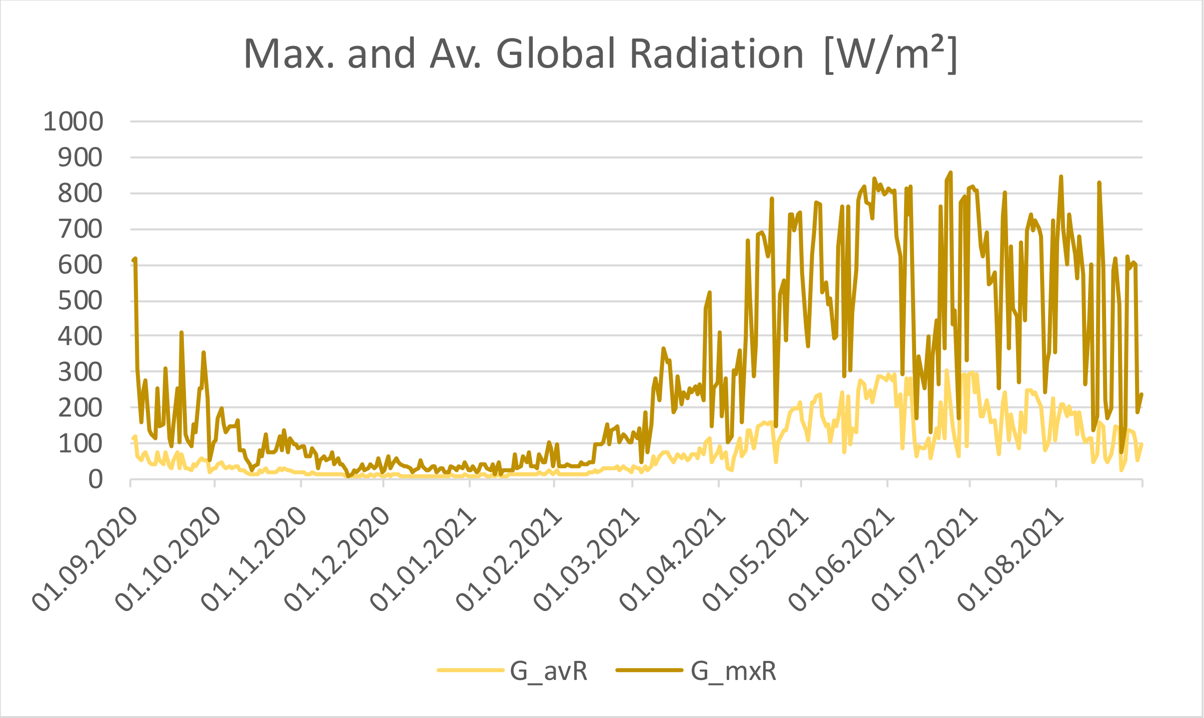
The dataset had several missing data due to problems with power supply, GSM modem connection and sensor failures. Unfortunately, all *Dusttrak*s were out of power supply for many months from winter to early summer 2020. Therefore, PM data are presented separately for two periods a) Sep—Nov 2020, and b) July—August 2021.

This technical report is based on preliminary results from an overview data analysis which followed simple statistical approaches (correlation analyses, multiple linear regressions, principle component analyses). As such, all interpretations only have hypothetical character, and will be subject to in-depth scientific procedures before scientific publication.

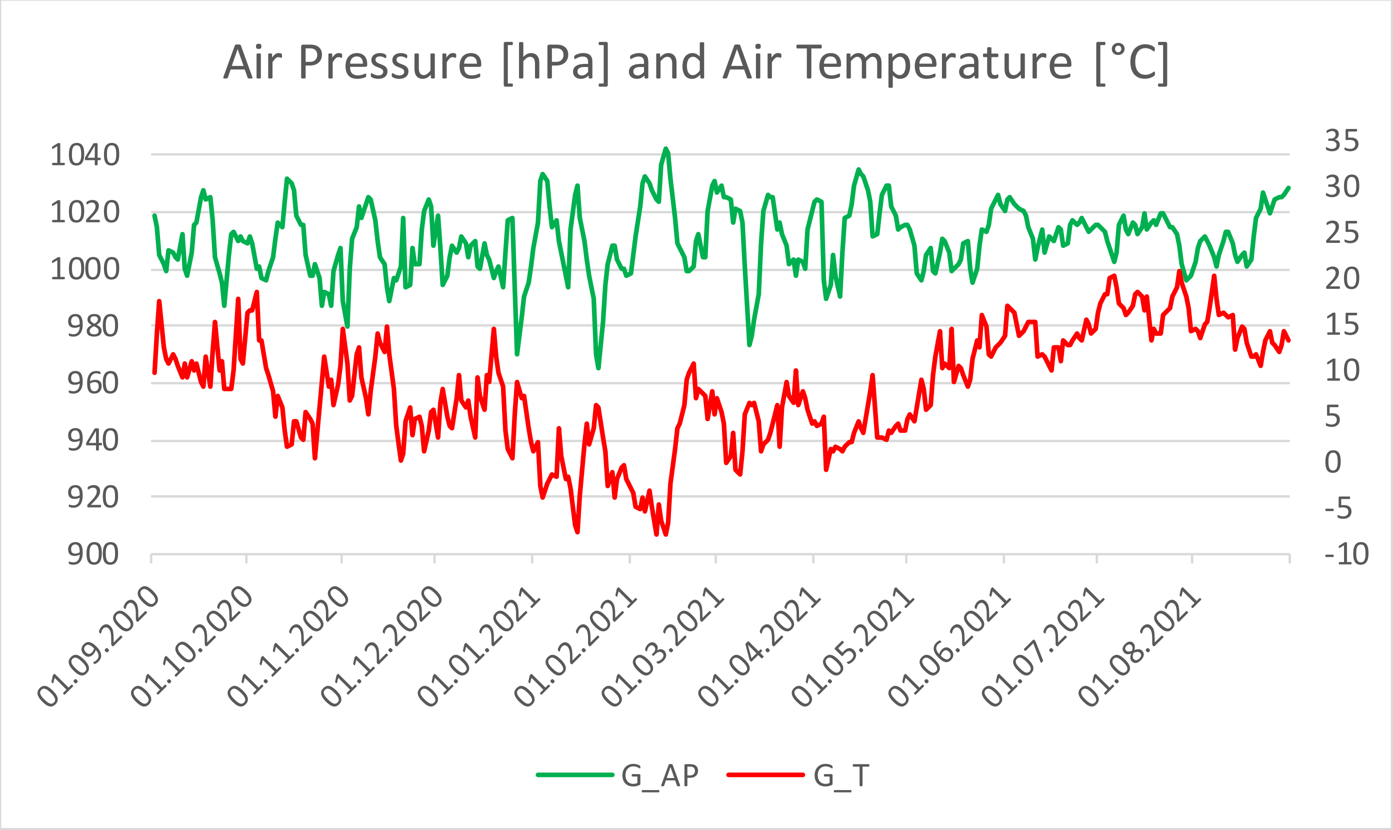
3. Results

3.1 Climate and Weather Conditions

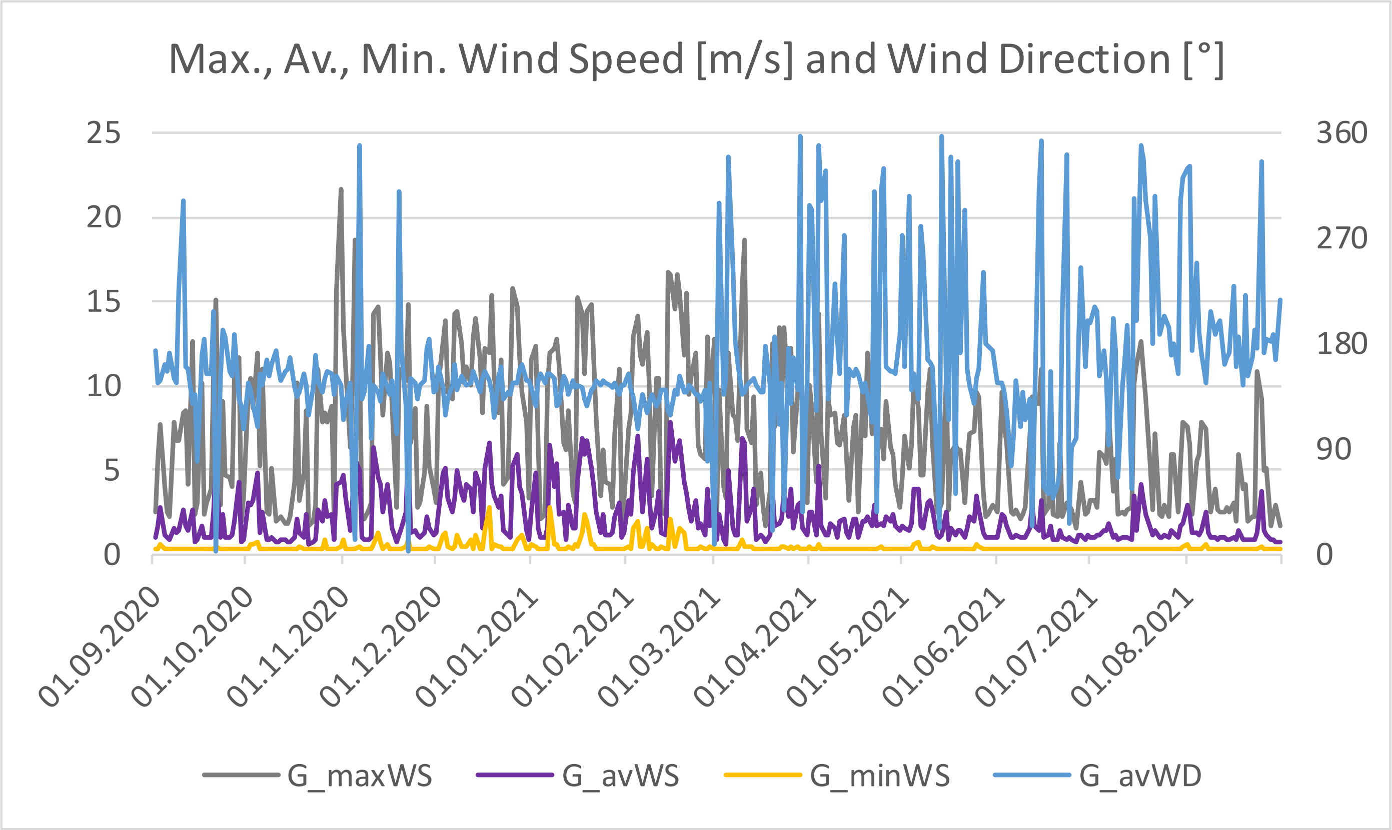
Solar radiation is special as to the northern latitude of about 62°N in combination with high (>1500 m) and steep mountains framing the location. As a result seasonality of direct sunlight is largely expressed. Mean daily radiation is low throughout the year but during cloudless summer days maximum radiation can be very intense, leading to high UV radiation which stimulates photochemical reactions in the near ground atmosphere. In 2021, mid of May until first week in June was a longer period of clear sky and thus intense short-wave radiation (in and out); the onset of radiation-driven air convection effects started in April, and there were periods with reduced radiation during the summer season due to cloud cover, especially in June. Longer periods in July and August were sunny.



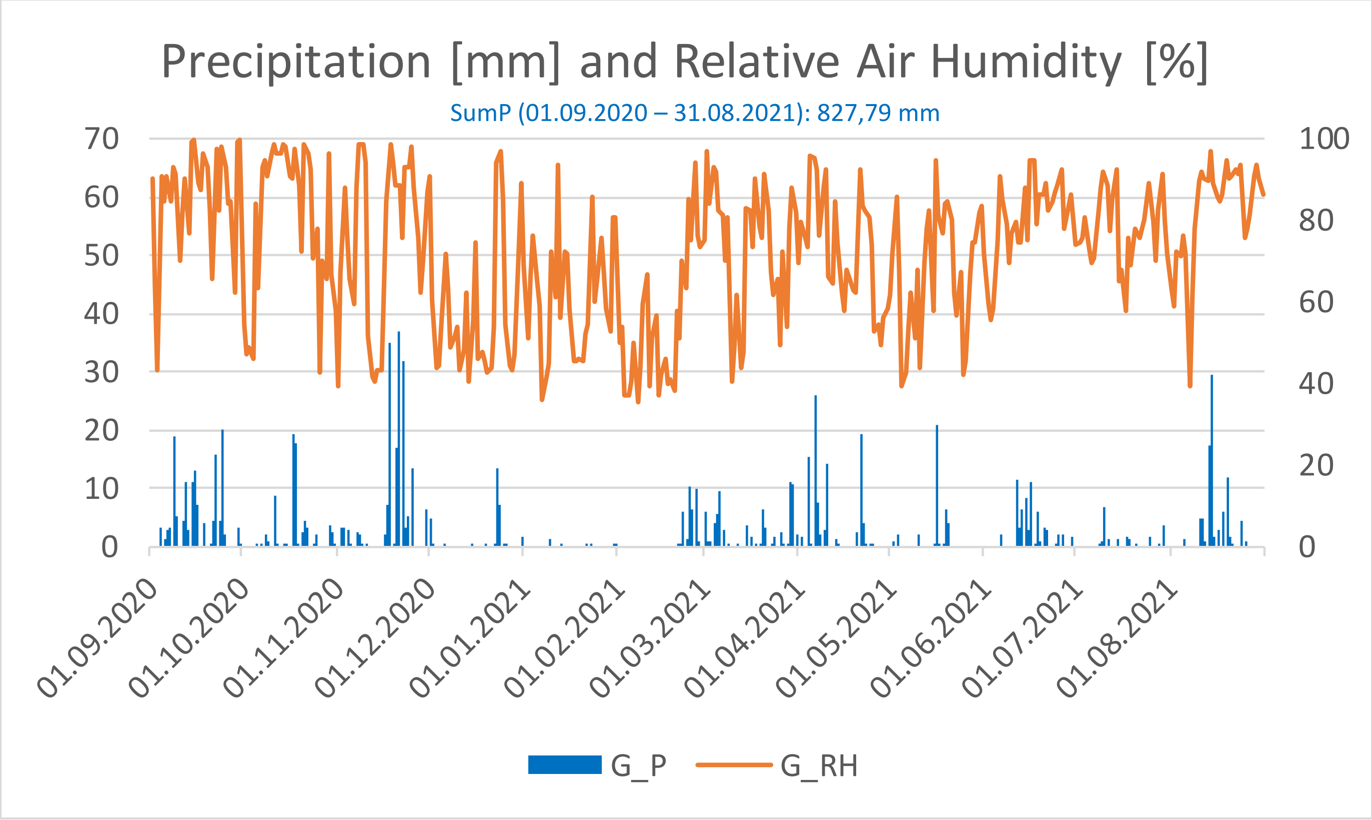
Air pressure and air temperature follow the course of the weather variability of the Atlantic north driven by Westerlies and Gulf Stream. The mountain topography has a predominantly expressed effect on temperature by a) the Foehn-Effect leading to falling warm dry winds from the South, when under low air pressure systems the mountains are blocking the south-western cyclones from the Atlantic ocean, and b) Nocturnal Cold Air Flow usually in combination with expressed high pressure systems and resulting inversion climate, which leads to relatively low temperatures in the valley bottom. In 2021, high pressure occurred during the winter periods in January, March and April. Low pressure periods were restricted to shorter periods during September—February and March—April. Temperatures were constantly rising from the beginning auf May until July; continuous convective circulation and inversion climate were well expressed for longer periods during the entire summer period.



Wind directions are from the South mainly, with a variety of modifications from more eastern or western components. As to the direction of the valley southern winds are strongest, especially in winter. But there is a high variability of wind conditions, and stable and constant winds are rare over longer periods. Wind speeds are very low during inversion weather, while during foehn the winds speeds are highest with elevation decreasing to the valley bottom. During the report period southern winds (SSE) were dominant from September until February and the first two week in June. Longer periods from March to August had local wind directions originating from uphill convective air streams, nocturnal cold air streams and topographic varieties. Average and minimum wind speeds were very low especially during high pressure autochtonous weather. Overall storms from the West often expressed as local southern winds (foehn) were very seldom during 2021.



Precipitation is connected to the location in the northern Atlantic but varies locally along the elevation gradient, and temporally with seasons and from year to year. **Relative Air Humidity** is extremely variable with temperatures, but most pronounced under inversion climate and cold air streams in the summer period. In 2021, dry conditions were stable for long periods, and the report period had a very low total sum of precipitation. Unstable weather with cyclone activity were restricted to shorter periods during early winter. As a result, there was little snow in the mountains, and except short periods with rain, the report period was comparably dry. Daily average Air Humidity was constantly quite low from January until August 2021, resulting in high water pressure deficits. This might have led to site-specific drought.



3.2 Air Pollution by Particulate Matter

3.2.1 Absolute Concentration of Particulate Matter

Due to problems with power supply, there is a long period of missing data for PM during the report period. This limits interpretation of the remaining dataset and only allows drawing conclusions on short-term meachanisms.

Compared to the proposed daily limit of 15 µg/m³ $PM_{2.5}$ according to NPHI & NEA (2013), which is stricter than those suggested by the WHO (2005), our data show minor exceedances during short periods in October 2020 and July 2021 (see black arrows, p. 17).

The *Corona* situation had limited sea traffic in 2021, with cruise ship traffic restarting in August 2021. Bus traffic was also very limited. Daily ferry connections to Hellesylt started their regular schedule 12th May 2021. Hurtigruten entered the fjord on schedule (at port 13:15—13:30 GMT+1) from 1st June 2021. There were smaller local controlled open fire events (e.g. July 23rd July). Peak holiday season was coming with a lot of road traffic (cars and caravans) and outdoor activity due to "nice" weather (charcoal and wood combustion).

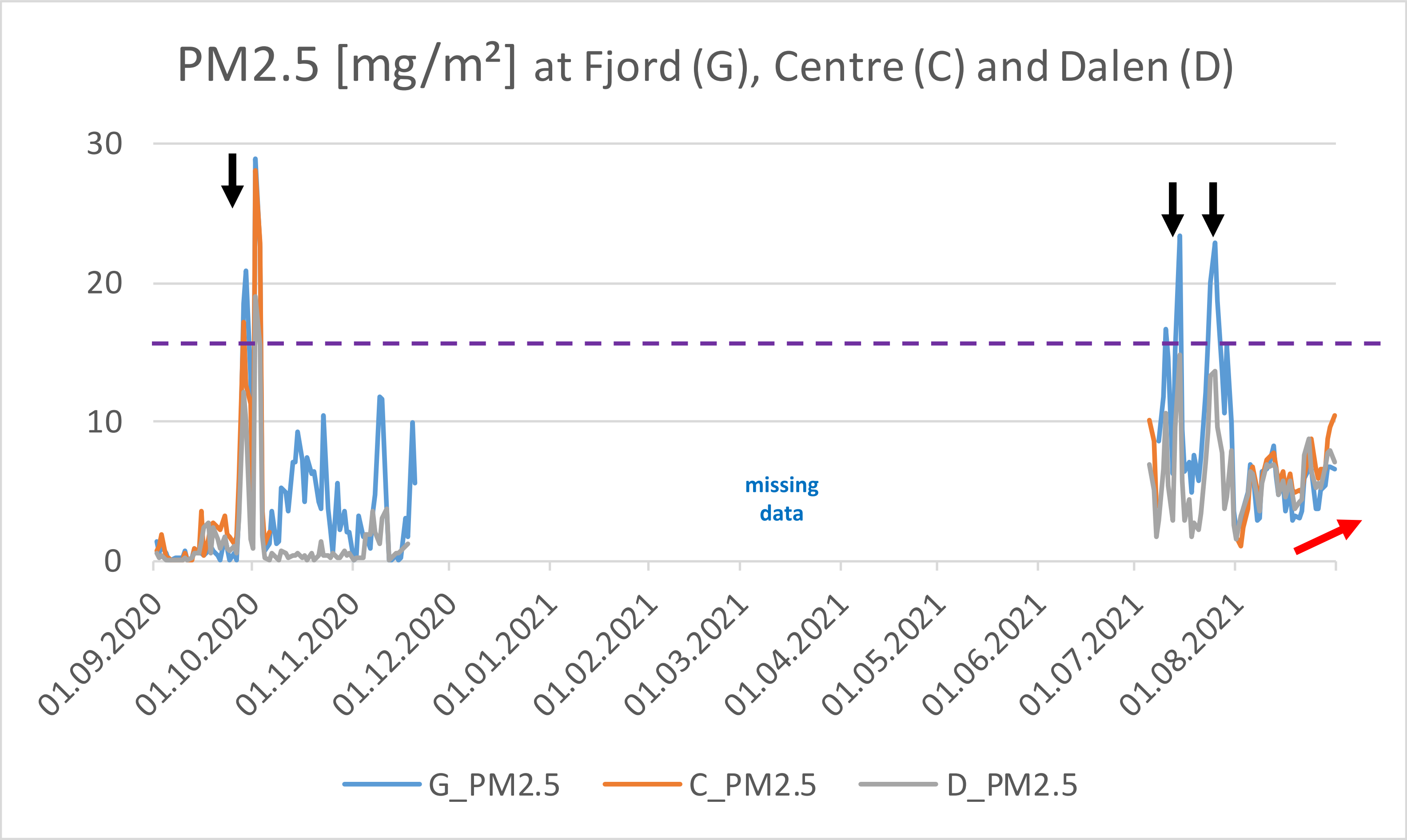
In Geiranger, there are a few emergency diesel generators in use, when electricity is down during winter. Heating houses is practiced by electricity and fire wood combustion.

The onset of the cruise traffic during autumn was accompanied with an constant increase of PM emissions, as expressed by the elevated minimum PM_1 level (indicated by the red arrow).

Both, short-term events (black arrows), and the effect of the onset of cruise traffic (red arrow) serve as ideal scientific experimental conditions. We will use these situations for a detailed interpretation and may verify previously assumed mechanisms behind the spatio-temporal air pollution patterns in the Geiranger Fjord (see chapter 3.5).

WHO [World Health Organization] (2005): Air quality guidelines - global update 2005.

NPHI [Norwegian Public Health Institute] & NEA [Norwegian Environment Agency] (2013): Luftkvalitetskriterier - Virkninger av luftforurensning på helse Rapport 2013: 9. Oslo.



NPHI & NEA (2013) Proposed Daily Limit = 15 µg/m³

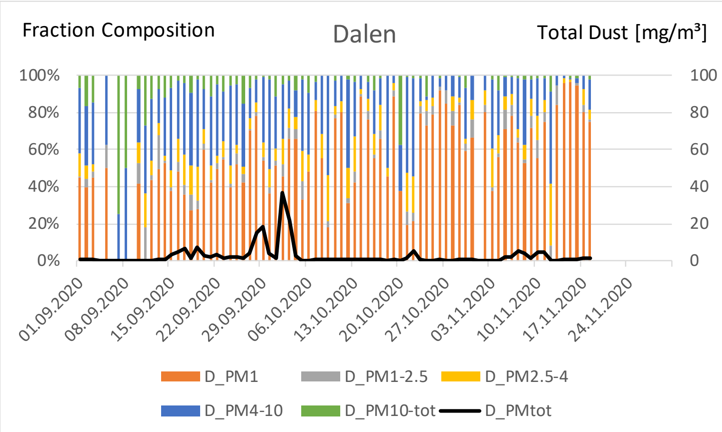
3.2.2 Fractions of Particulate Matter

Dust monitoring started in May 2015. Since, a cumulating effect on particulate matter (PM) concentrations was repeatedly reported. Cumulative effects during summer seemed to last at least for several weeks, and were visible also in the long-term over parts of the winter period. Here, although limited by the long period of missing data, we again argue about the mechanisms and try to prove our understanding. The following arguments are structured as follows: Fraction signature – co-occurrence with other pollutants – correlation with weather conditions.

Composition of different fractions in relation to the total dust measured (PM_{total}) at our three stations showed that the composition of the entire dust was driven by single events. In general, dust emission level was low during the entire report period. The fraction signature of the single larger emissions was different, e.g. the event at the end of September 2020 had typical diesel combustion signature (high PM_1 proportion), whereas the event at the beginning of October 2020 had a different signature (lower PM_1 proportions, higher coarser dust proportions), most likely attributed to wood combustion. During the following weeks in October and November, PM_1 signatures increase throughout the elevational gradient, while the entire PM concentrations only increased at lowest elevation, compared to the previous period. As such, long residence times of the finest fraction of PM are evident.

Again, the major fraction of the dust was shown to be the finest particulates which mainly originate from diesel combustion. This in combination with relatively high values of PM_1 along the entire elevational gradient confirms that the mechanisms are 4-dimensional and the entire turbulent air volume of the valley is concerned. The turbulent air volume might therefore need months to fully recover from PM contamination.

During July and August 2021, PM_1 fraction signatures were most pronounced at higher elevations (Dalen) than at our two lower stations (p. 19). Total dust levels were quite low throughout the summer, but single events had impact on the entire air volume, as expressed be the +/- synchronous PM_1 curves at Fjord and Dalen stations. These single events were attributed to ship emissions (see evidence from co-occurrence of gasses and PM, chapter 3.4), and specific weather conditions directed the emissions from the fjord to the south (see chapter 3.5). Elevated PM concentrations during July were most likely originating from Hurtigruten/Ferry/site-seeing ship emissions. Late August concentrations also might have originated from cruise ship emissions, which were not yet well expressed in the short-term. We thus expect to see the cruise ship signatures during the later course of the autumn and will address this issue in the AQ report of next year.


Fraction Composition
Dalen
Total Dust [mg/m³]
100%
80%
60%
40%
20%
0%
100
80
60
40
20
0
01.09.2020
08.09.2020
15.09.2020
22.09.2020
29.09.2020
06.10.2020
13.10.2020
20.10.2020
27.10.2020
03.11.2020
10.11.2020
17.11.2020
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D_PM1
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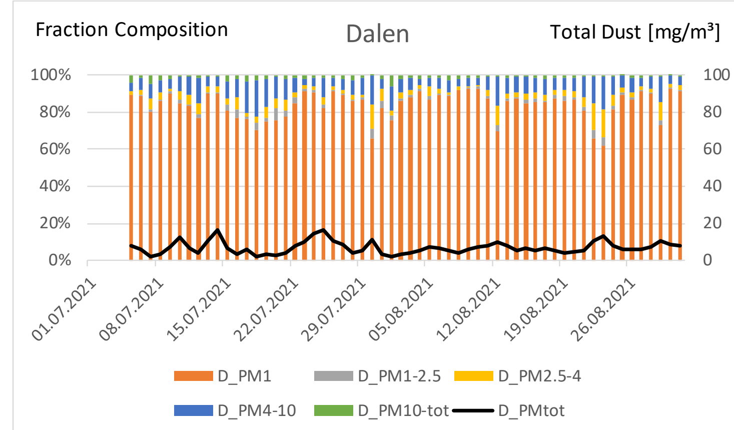
D_PM2.5-4
D_PM4-10
D_PM10-tot
D_PMtot


Fraction Composition
Dalen
Total Dust [mg/m³]
100%
80%
60%
40%
20%
0%
100
80
60
40
20
0
01.07.2021
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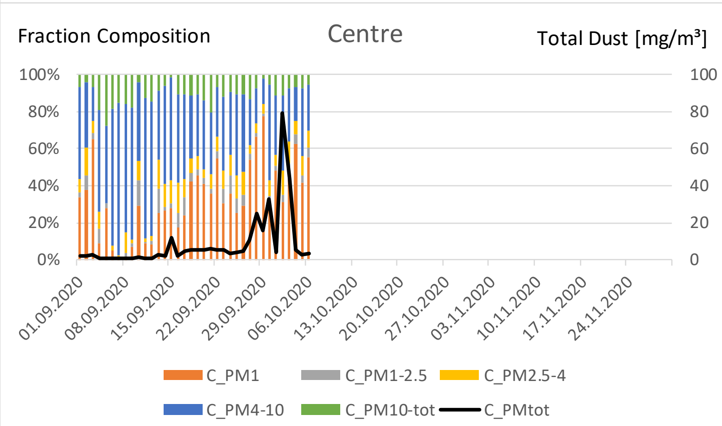
29.07.2021
05.08.2021
12.08.2021
19.08.2021
26.08.2021
D_PM1
D_PM1-2.5
D_PM2.5-4
D_PM4-10
D_PM10-tot
D_PMtot


Fraction Composition
Centre
Total Dust [mg/m³]
100%
80%
60%
40%
20%
0%
100
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01.09.2020
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27.10.2020
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10.11.2020
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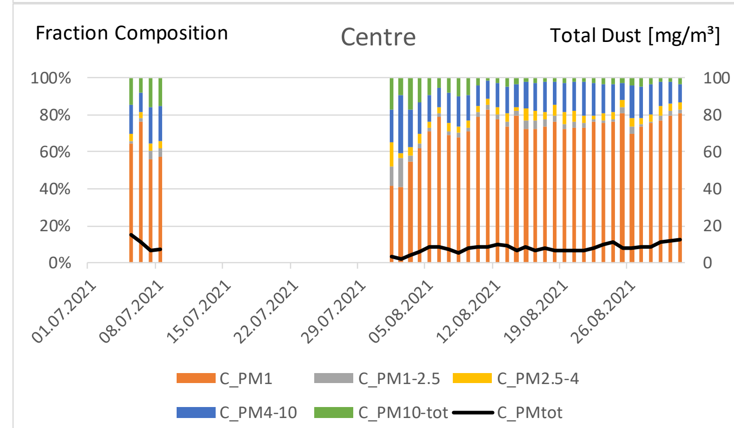
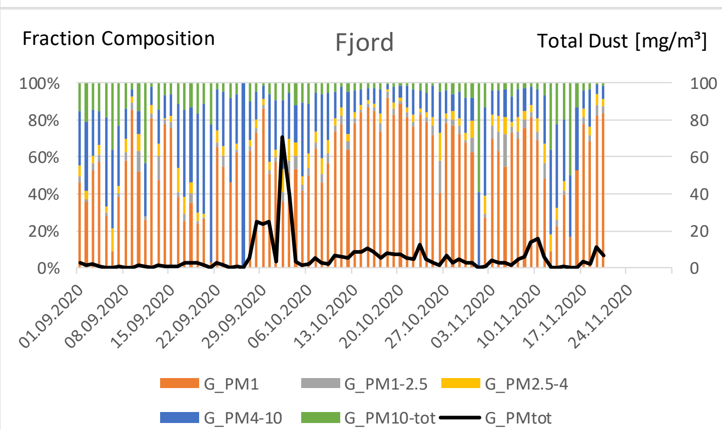
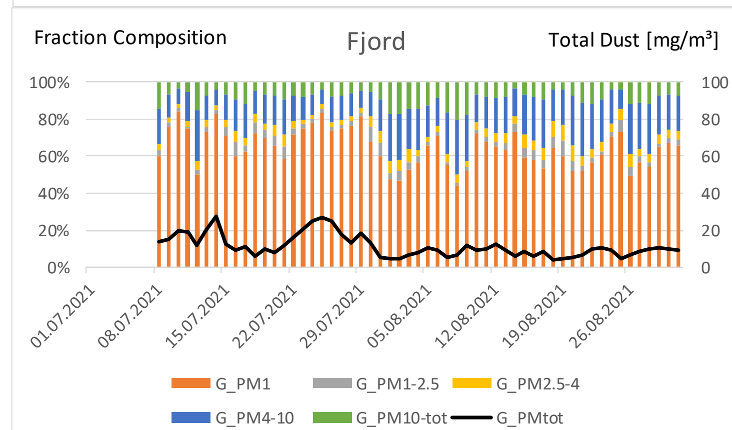
C_PM2.5-4
C_PM4-10
C_PM10-tot
C_PMtot


Fraction Composition
Centre
Total Dust [mg/m³]
100%
80%
60%
40%
20%
0%
100
80
60
40
20
0
01.07.2021
08.07.2021
15.07.2021
22.07.2021
29.07.2021
05.08.2021
12.08.2021
19.08.2021
26.08.2021
C_PM1
C_PM1-2.5
C_PM2.5-4
C_PM4-10
C_PM10-tot
C_PMtot


Fraction Composition
Fjord
Total Dust [mg/m³]
100%
80%
60%
40%
20%
0%
100
80
60
40
20
0
01.09.2020
08.09.2020
15.09.2020
22.09.2020
29.09.2020
06.10.2020
13.10.2020
20.10.2020
27.10.2020
03.11.2020
10.11.2020
17.11.2020
24.11.2020
G_PM1
G_PM1-2.5
G_PM2.5-4
G_PM4-10
G_PM10-tot
G_PMtot


Fraction Composition
Fjord
Total Dust [mg/m³]
100%
80%
60%
40%
20%
0%
100
80
60
40
20
0
01.07.2021
08.07.2021
15.07.2021
22.07.2021
29.07.2021
05.08.2021
12.08.2021
19.08.2021
26.08.2021
G_PM1
G_PM1-2.5
G_PM2.5-4
G_PM4-10
G_PM10-tot
G_PMtot

3.3 Air Pollution by Gases

Gas emission data from 2021 were recorded throughout the report period (only minor missing data), compared to the long period of missing data from PM measurements.

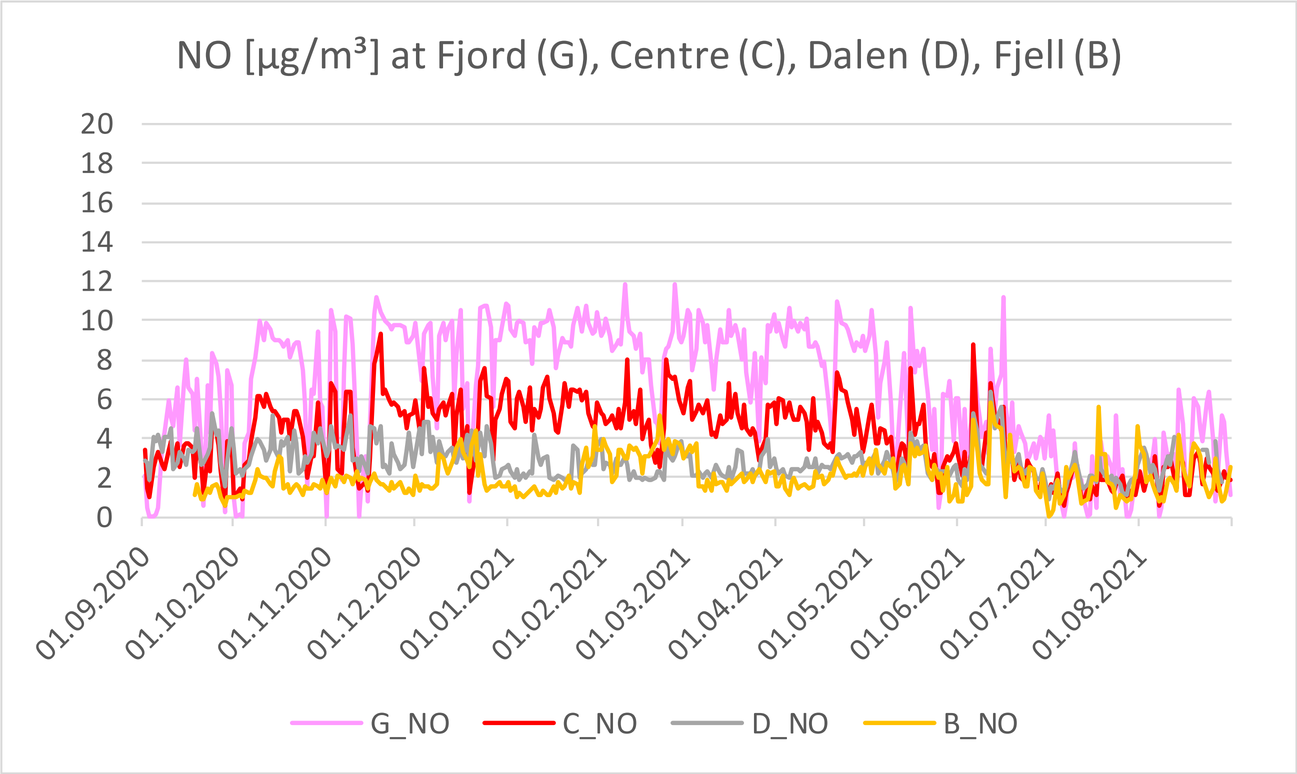
3.3.1 Air Pollution by NO and NO_2 (NO_x)

Nitric Oxide (NO) was low during the entire period. There were very low levels of constant NO concentrations at all four stations, and below 5 µg/m³ at the higher elevations, which is around the trace limit with our equipment.

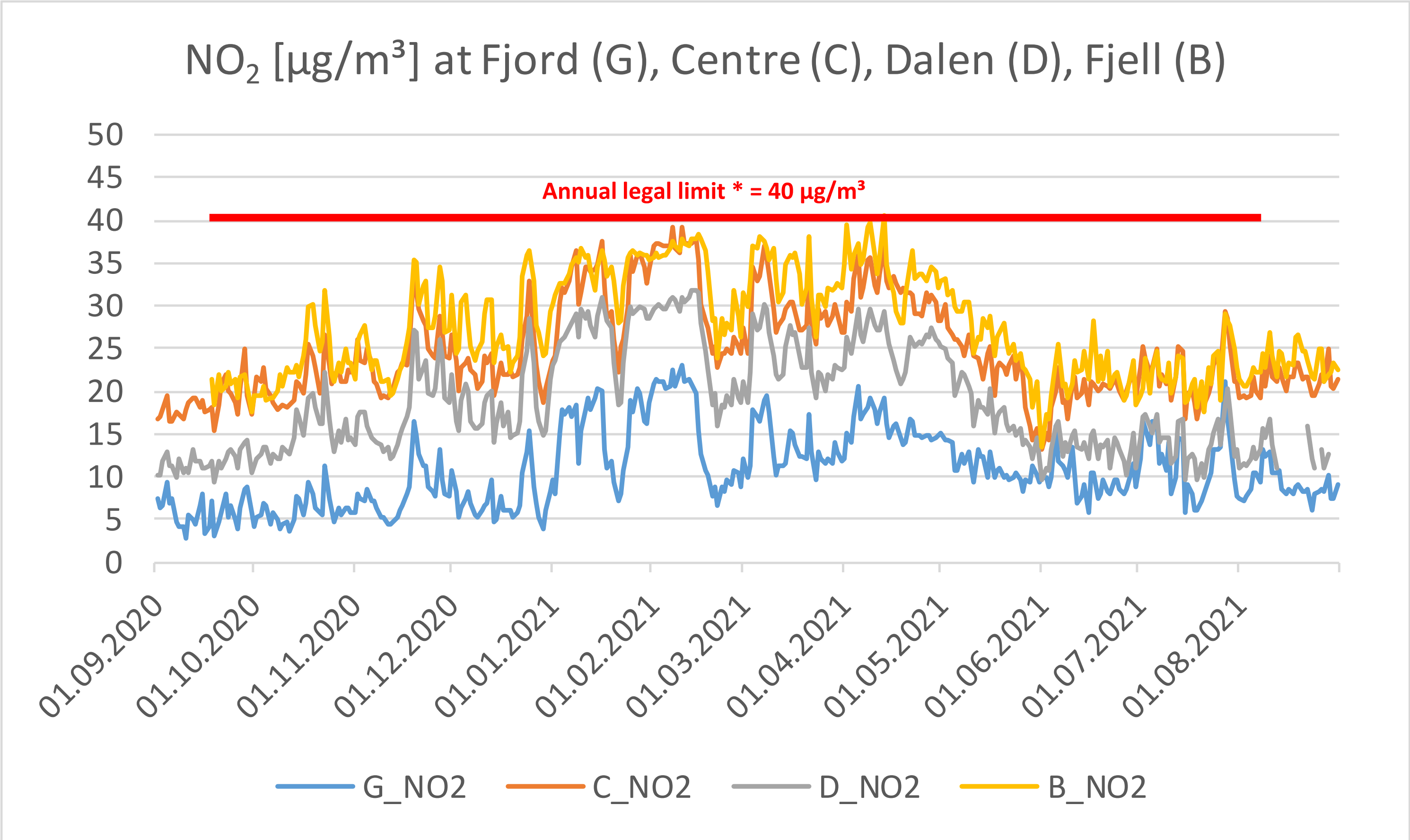
Nitrogen Dioxide (NO_2) was far below the Norwegian legal hourly limit of 200 µg/m³, and never exceeded the suggested limit of 100 µg/m³ (NPHI & NEA (2013) at any station in the area. In contrary to NO, which had a very short residence time after exposure, NO_2 accumulated in the entire air volume of the valley throughout longer periods. The cumulative annual amount of NO_2 is at about 50% of the legal limit.

Interestingly, here our data show that winter emissions (especially exposed during the cold periods) had a stronger impact on overall NO_2 contamination than emissions during summer period under *Corona* conditions.

In total, NO and NO_2 sum up to the concentration of NO_x to the air pollution of the Geiranger area. NO_x as such will in an annual perspective most probably contribute to higher impact on the vegetation. This will especially impact on the ecosystems which are naturally nitrogen limited, and where long-term anthropogenic nitrogen input has accumulated in the above- and below-ground biomass over decades already.



NO [µg/m³] at Fjord (G), Centre (C), Dalen (D), Fjell (B)
20
18
16
14
12
10
8
6
4
2
0
01.09.2020
01.10.2020
01.11.2020
01.12.2020
01.01.2021
01.02.2021
01.03.2021
01.04.2021
01.05.2021
01.06.2021
01.07.2021
01.08.2021
G_NO
C_NO
D_NO
B_NO



B (Annual Average) = 27,5 µg/m³
D (Annual Average) = 18,8 µg/m³
C (Annual Average) = 24,8 mg/m³
G (Annual Average) = 10,8 µg/m³

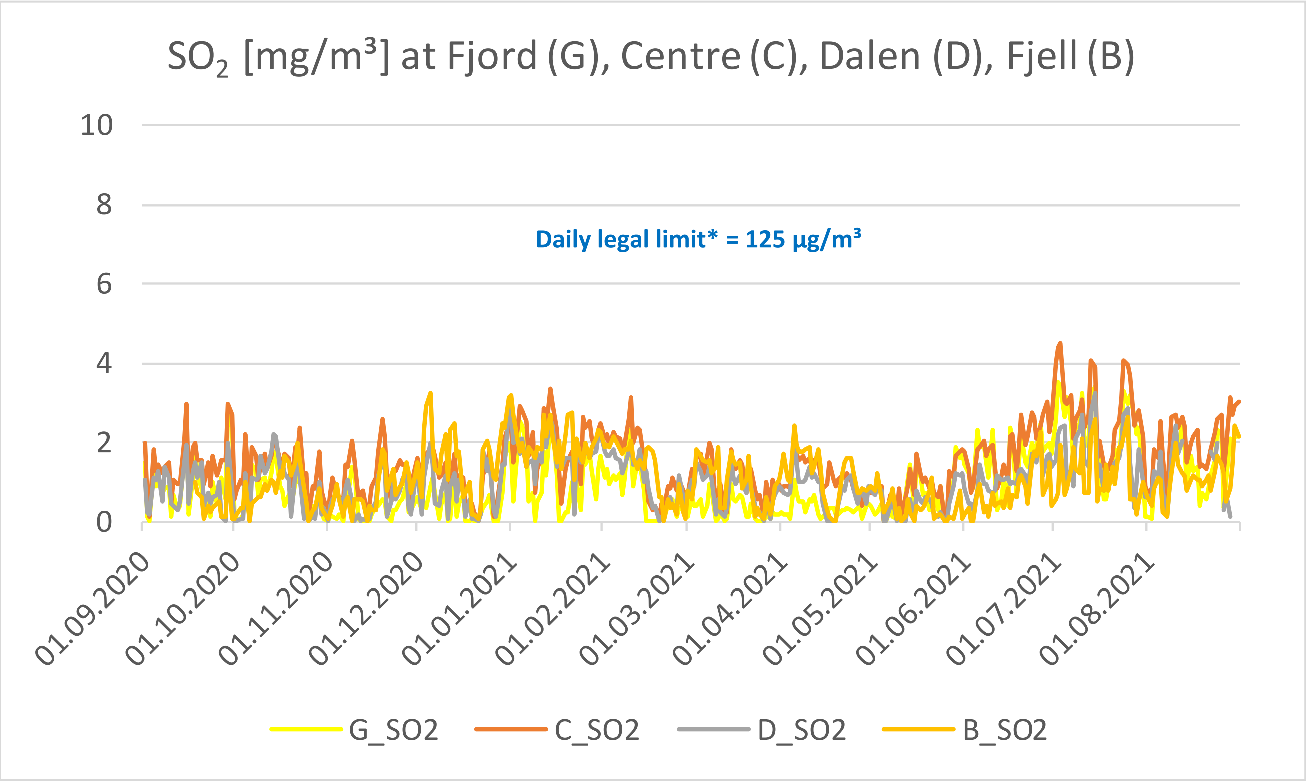
* The Ministry of Climate and Environment (2004): Forskrift om begrensning av forurensning (forurensningsforskriften) FOR 2004-06-01. http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20040601-0931.html#map040 (03.10.2017).

3.3.2 Air Pollution by SO_2

Sulphur Dioxide (SO_2) pollution in during the report period was very low at daily average at all four elevations.

Still, there is traceable SO_2 in the air, which is a good indicator of the origin of emissions. We here assume that fuel used in road traffic is +/- free of SO_2 and heavy diesel oil is the only major source of SO_2.

Our data show a slightly elevated Sulphur level during the summer period, in periods twice as high as during the winter reference period, and SO_2 concentrations at different stations follow a +/- simultaneous pattern. As such, we might use this signature to trace the emissions from ship fuel combustion (see chapter 3.4).



Annual legal limit* = 20 µg/m³

B (Annual Average) = 1,1 µg/m³

D (Annual Average) = 1,0 µg/m³

C (Annual Average) = 1,5 mg/m³

G (Annual Average) = 0,9 µg/m³

* The Ministry of Climate and Environment (2004): Forskrift om begrensning av forurensning (forurensningsforskriften) FOR 2004-06-01. http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20040601-0931.html#map040 (03.10.2017).

3.4 Co-Occurrence of Gases and PM

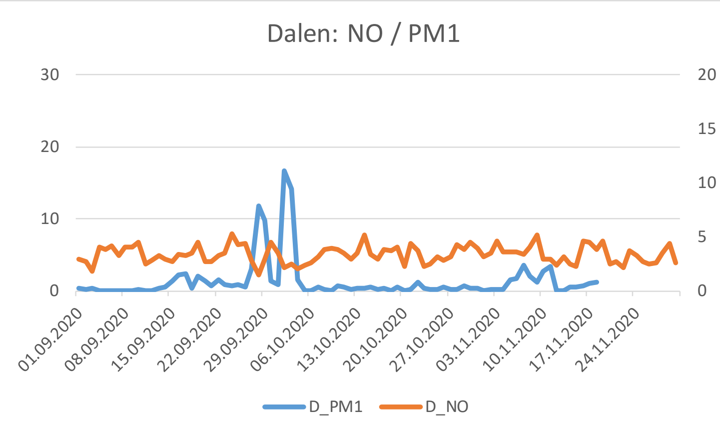
PM_1 signatures alone were most pronounced at the fjord level, and we argue that they might be used to trace mature particles (and other types of emissions from active combustion, if any).

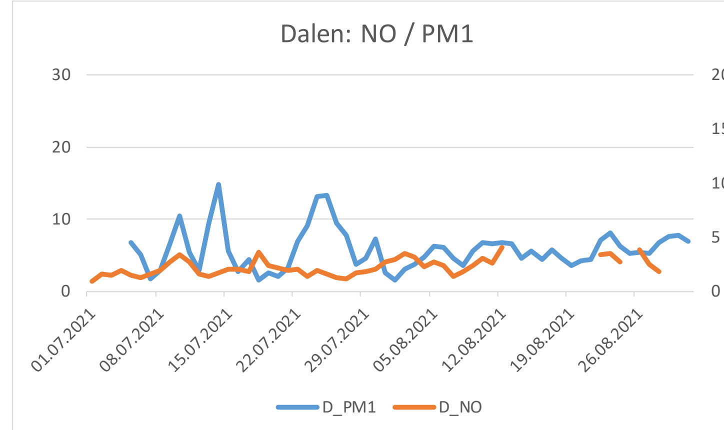
NO has a very short residence time (< 2 days), reaction to NO_2 is fast, but may be reversed in the presence of ozone, which is depending on daytime UV-initiated chain reactions. NO emissions are very low during the entire reporting period. There were constant low levels of NO at all four stations. Our data indicate very little combustion in engines. NO signatures are decoupled from PM signatures for the majority of different periods, which suggests that synchronicity between both is a good indicator of immediacy effects.

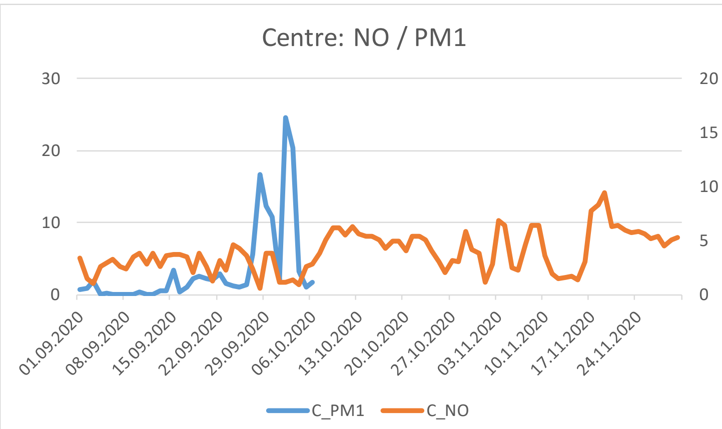
NO_2 has a short residence time (< 1 week), but there is no wash-out effect by precipitation. Our data show low absolute values over the entire report period, with a maximum plateau effect during the winter. Like above, there is no expressed synchronicity of PM and NO_2 concentration patterns, which suggests PM concentrations even being decoupled from short-term emission dynamics.

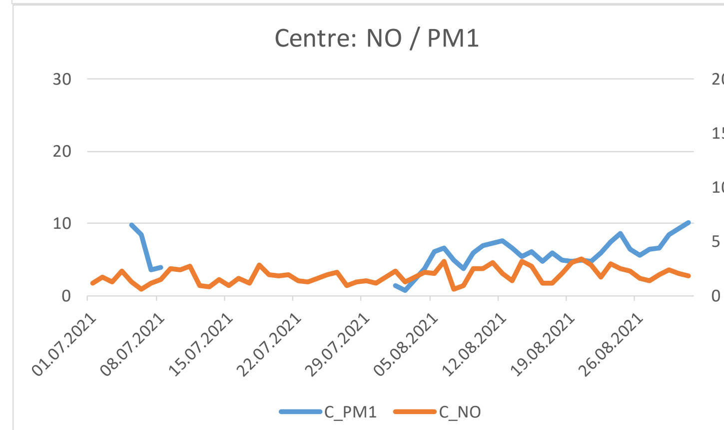
Our data show significant SO_2 signatures which mainly trace (raw) diesel combustion during the summer period of 2021; its residence time (< 2 weeks) is much shorter than that of PM_1 (months). There is an immediate wash-out effect on SO_2 by precipitation (hours). We had clearly coupled PM_1/SO_2 signatures in our time series which allowed tracing the event of combustion and short-term distribution of emissions. The statistical evidence of its synchronicity with PM concentration patterns suggests PM mainly being driven at this time scale!

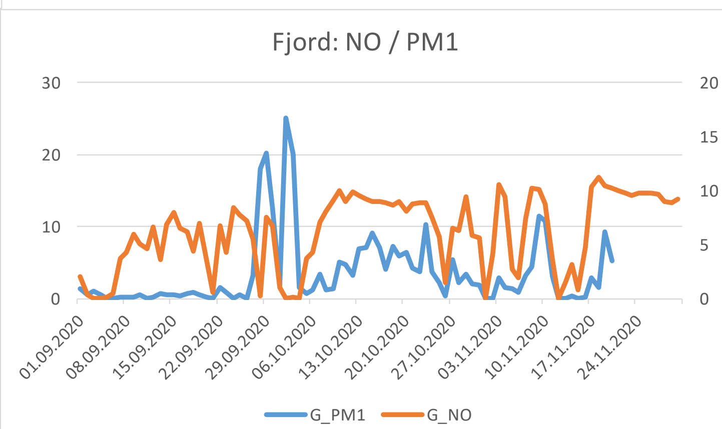
During end of September 2020, the coupled Sulphur/PM signature indicated emissions from diesel combustion; the signature from the following event at the beginning of October 2020 with higher PM emissions indicated non-diesel combustion. Here, the dataset lost statistical evidence as to complex PM sources.

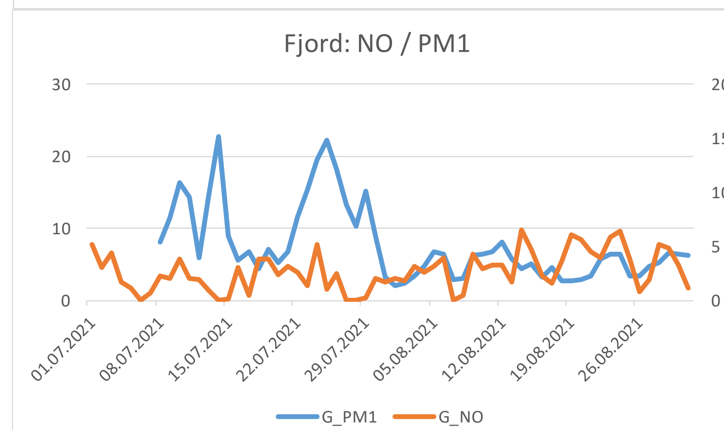

Dalen: NO / PM1
30
20
10
0
20
15
10
5
0
01.09.2020
08.09.2020
15.09.2020
22.09.2020
29.09.2020
06.10.2020
13.10.2020
20.10.2020
27.10.2020
03.11.2020
10.11.2020
17.11.2020
24.11.2020
D_PM1
D_NO

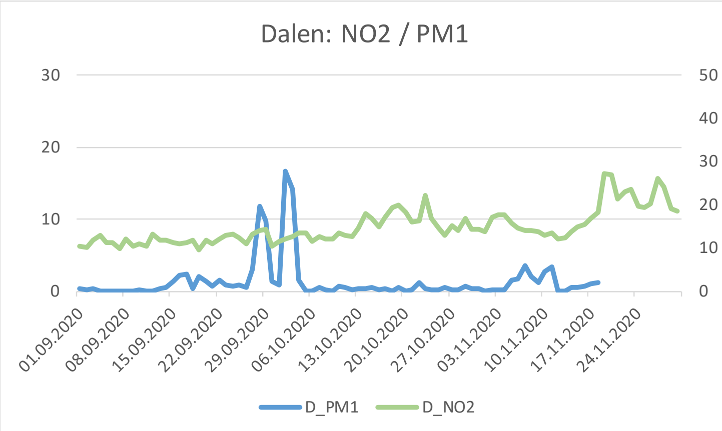

Dalen: NO / PM1
30
20
10
0
20
15
10
5
0
01.07.2021
08.07.2021
15.07.2021
22.07.2021
29.07.2021
05.08.2021
12.08.2021
19.08.2021
26.08.2021
D_PM1
D_NO

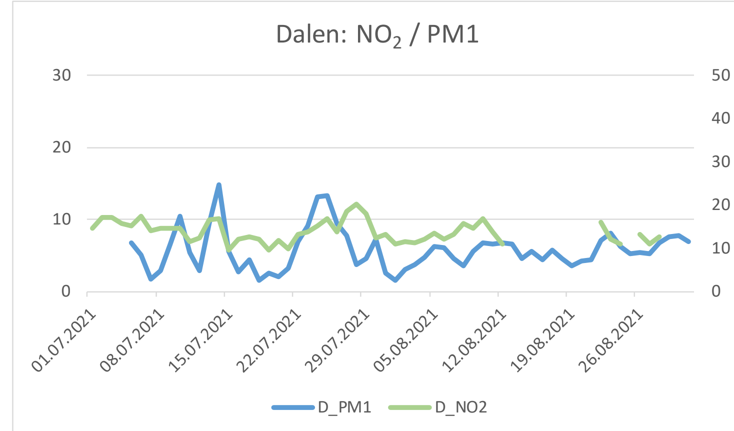

Centre: NO / PM1
30
20
10
0
20
15
10
5
0
01.09.2020
08.09.2020
15.09.2020
22.09.2020
29.09.2020
06.10.2020
13.10.2020
20.10.2020
27.10.2020
03.11.2020
10.11.2020
17.11.2020
24.11.2020
C_PM1
C_NO

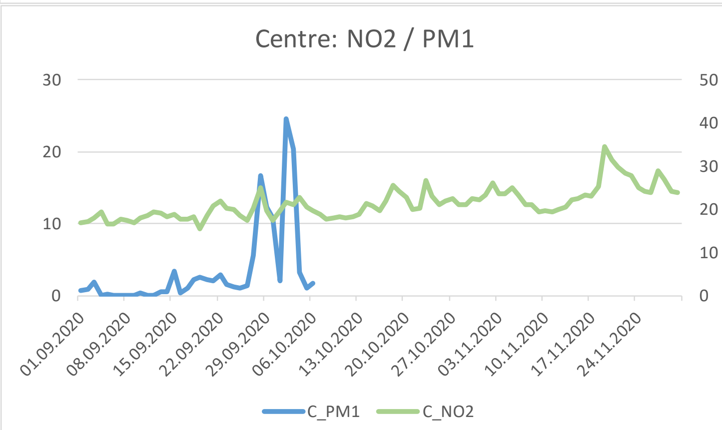

Centre: NO / PM1
30
20
10
0
20
15
10
5
0
01.07.2021
08.07.2021
15.07.2021
22.07.2021
29.07.2021
05.08.2021
12.08.2021
19.08.2021
26.08.2021
C_PM1
C_NO

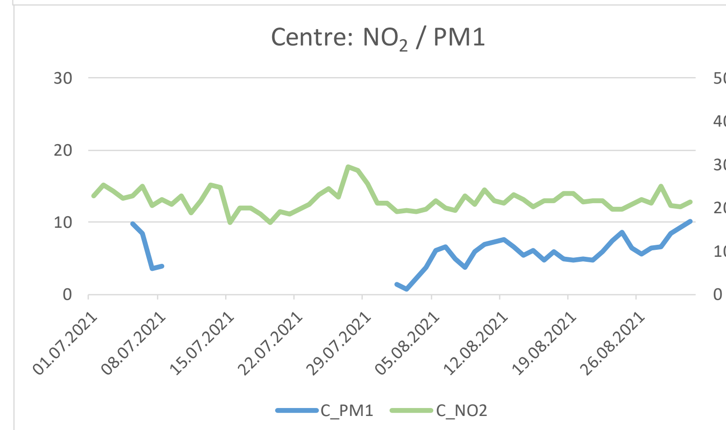

Fjord: NO / PM1
30
20
10
0
20
15
10
5
0
01.09.2020
08.09.2020
15.09.2020
22.09.2020
29.09.2020
06.10.2020
13.10.2020
20.10.2020
27.10.2020
03.11.2020
10.11.2020
17.11.2020
24.11.2020
G_PM1
G_NO

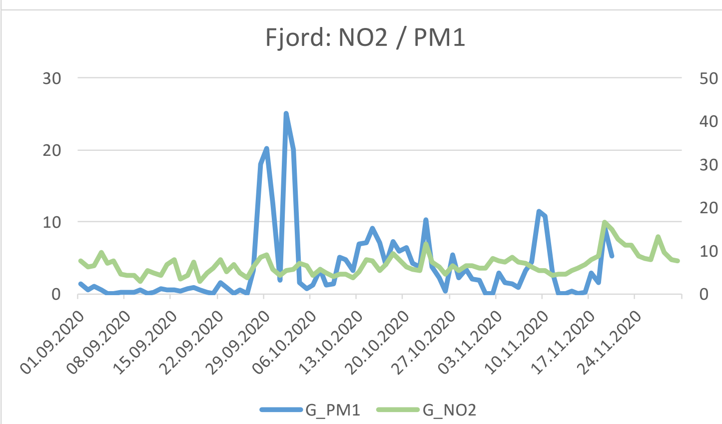

Fjord: NO / PM1
30
20
10
0
20
15
10
5
0
01.07.2021
08.07.2021
15.07.2021
22.07.2021
29.07.2021
05.08.2021
12.08.2021
19.08.2021
26.08.2021
G_PM1
G_NO

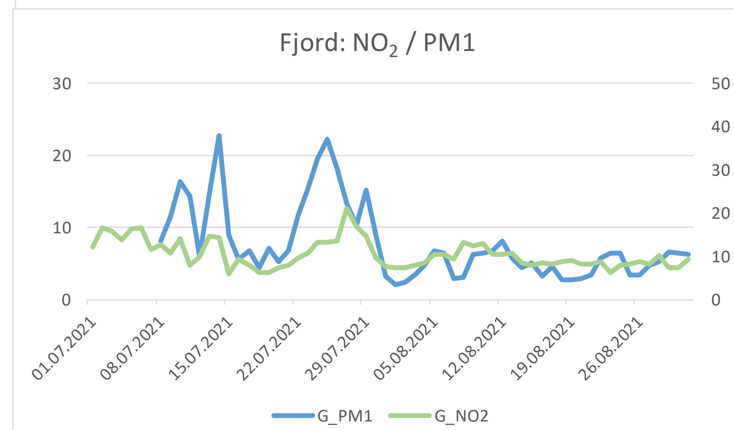

Dalen: NO2 / PM1
D_PM1
D_NO2

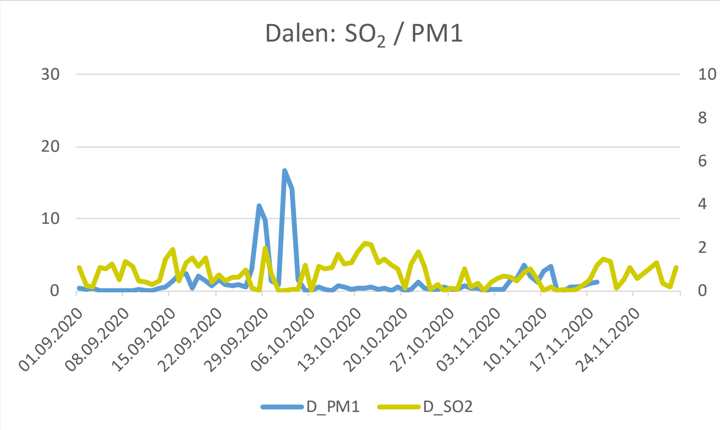

Dalen: NO2 / PM1
D_PM1
D_NO2

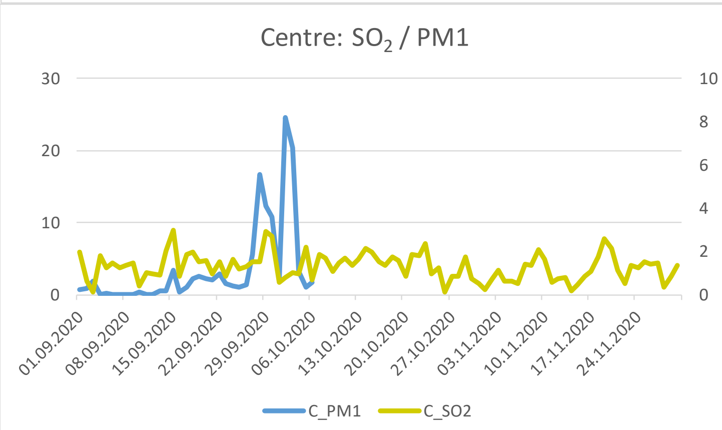

Centre: NO2 / PM1
C_PM1
C_NO2

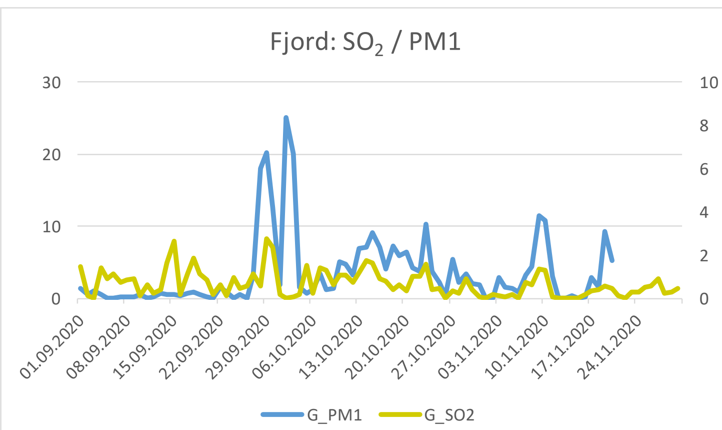

Centre: NO2 / PM1
C_PM1
C_NO2

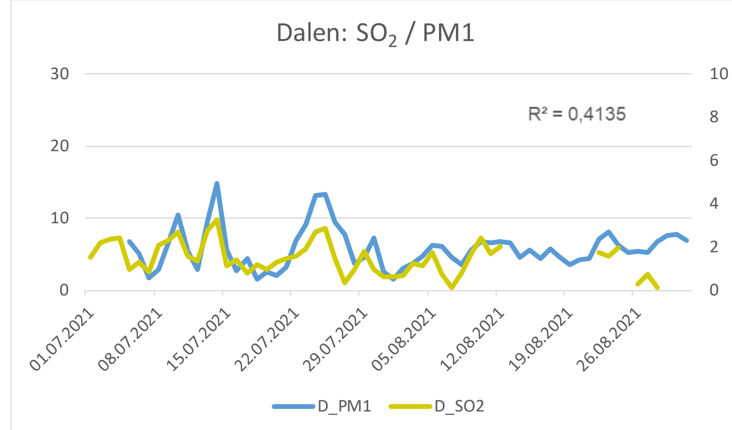

Fjord: NO2 / PM1
G_PM1
G_NO2

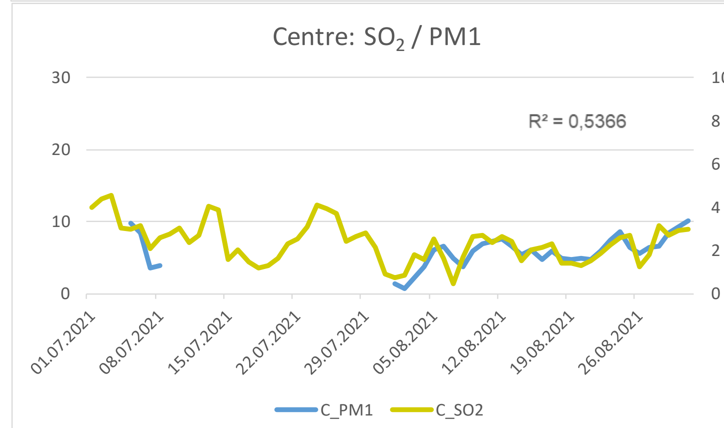

Fjord: NO2 / PM1
G_PM1
G_NO2

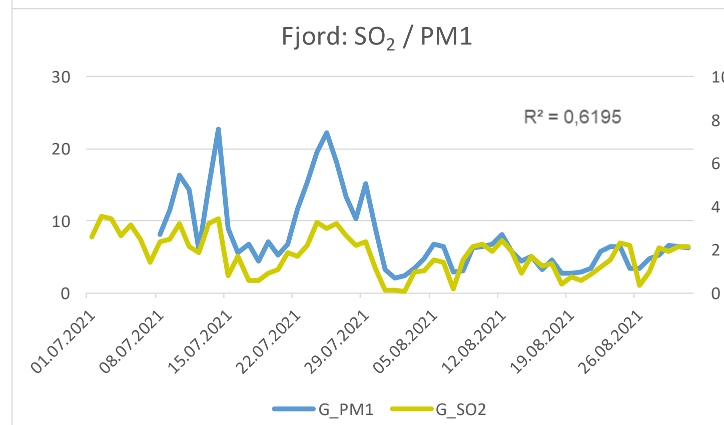

Dalen: SO2 / PM1
30
20
10
0
10
8
6
4
2
0
01.09.2020
08.09.2020
15.09.2020
22.09.2020
29.09.2020
06.10.2020
13.10.2020
20.10.2020
27.10.2020
03.11.2020
10.11.2020
17.11.2020
24.11.2020
D_PM1
D_SO2


Centre: SO2 / PM1
30
20
10
0
10
8
6
4
2
0
01.09.2020
08.09.2020
15.09.2020
22.09.2020
29.09.2020
06.10.2020
13.10.2020
20.10.2020
27.10.2020
03.11.2020
10.11.2020
17.11.2020
24.11.2020
C_PM1
C_SO2


Fjord: SO2 / PM1
30
20
10
0
10
8
6
4
2
0
01.09.2020
08.09.2020
15.09.2020
22.09.2020
29.09.2020
06.10.2020
13.10.2020
20.10.2020
27.10.2020
03.11.2020
10.11.2020
17.11.2020
24.11.2020
G_PM1
G_SO2


Dalen: SO2 / PM1
R² = 0,4135
30
20
10
0
10
8
6
4
2
0
01.07.2021
08.07.2021
15.07.2021
22.07.2021
29.07.2021
05.08.2021
12.08.2021
19.08.2021
26.08.2021
D_PM1
D_SO2


Centre: SO2 / PM1
R² = 0,5366
30
20
10
0
10
8
6
4
2
0
01.07.2021
08.07.2021
15.07.2021
22.07.2021
29.07.2021
05.08.2021
12.08.2021
19.08.2021
26.08.2021
C_PM1
C_SO2


Fjord: SO2 / PM1
R² = 0,6195
30
20
10
0
10
8
6
4
2
0
01.07.2021
08.07.2021
15.07.2021
22.07.2021
29.07.2021
05.08.2021
12.08.2021
19.08.2021
26.08.2021
G_PM1
G_SO2

3.5 Air Quality Variables and Explanatory Weather Variables

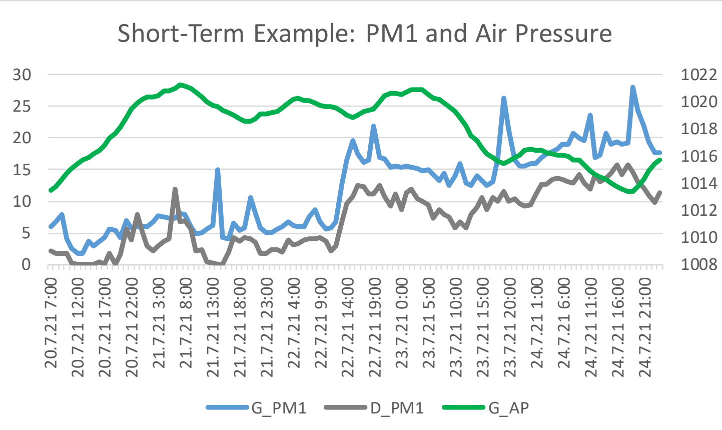
Impact of weather conditions on the dynamics of the pollutants proved to be complex. The new results from the 2020/21 period again underline this complexity, using an example from the summer 2021, only. This short period serves a perfect experiment, in which cruise emissions can be ruled out, and Hurtigruten, ferries and site-seeing ships are the only potential source for heavy oil combustion, for which a specific SO_2/PM signature is evident.

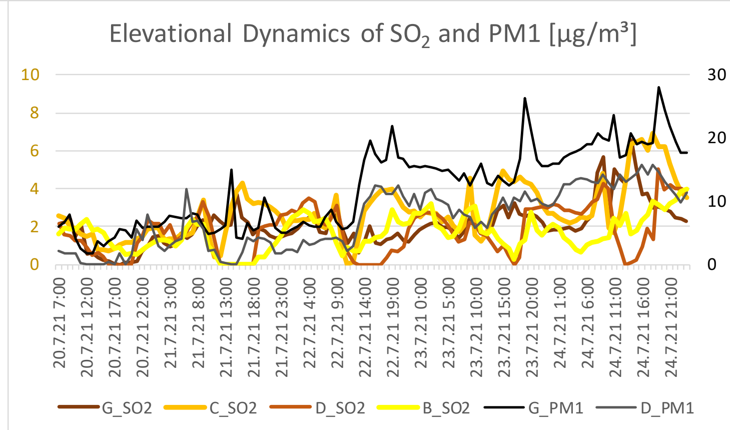
During the test period, high air pressure, very low wind speed, and variable winds from South and North were given. Cloud cover and air humidity were low (no precipitation). Due to a relatively low elevation inversion layer, the air volume into which ship emissions were exposed was small, so that absolute low amounts of emissions could have a maximum effect on concentrations of our air quality variables.

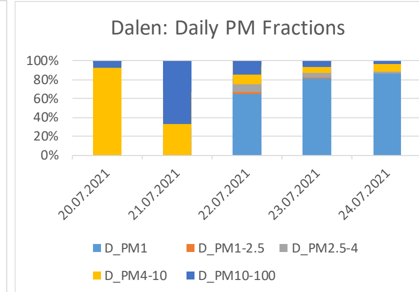
When wind was from the South, emissions were blown away from Geiranger village and from our experimental elevational gradient. When wind changed to northern directions, emissions exposed at the fjord were moved to the south, reaching our sensors along the entire gradient. Low wind speeds do not turbulently mix the air volume, so that immediate concentrations remain high in ascending air masses. This situation is very common under such specific weather conditions, and has often been documented visually following the smoke from the ships. As a consequence from the inversion layer, the emissions are brought upslope while being trapped in a certain limited air volume. After turbulent mixture, the emissions are slowly dispersed along the entire lower value, being brought back to lower elevations by combined effects of nocturnal cold-air streams (with and without fresh air surplus) and convective turbulence in complex topography. Under stabile weather conditions this mechanism might repeat over several days, with cumulative effects on the absolute concentrations of pollutants.

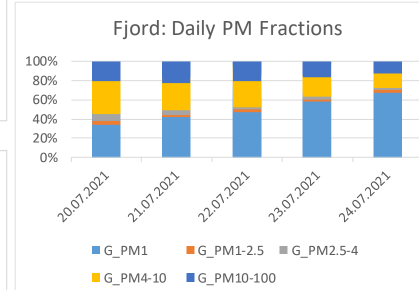
Our daily PM fractions at two different elevational levels nicely illustrate, how this continuous mechanism results in proceeding higher proportions of PM_1. The temporal dimension of this sequence perfectly corresponds with the spatial dimension: Expose to the air volume, PM primarily moves upwards, reaches highest concentrations below the assumed inversion layer (approx. 300—1200 m a.s.l.), and descends slowly back to fjord level with absolutely lower proportions after permanent turbulent mixture in the entire air volume, and might persist over many days.

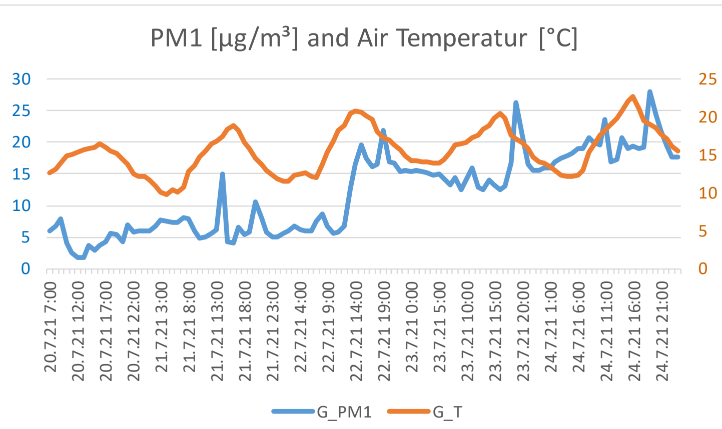
In this experiment, SO_2 serves as a tracer for the origin and the age of the emission at different positions. Although air pressure decreased towards the end of this period, opening space for larger air volumes engaged, while air temperatures further increased slightly, the pollutions patterns remains consistent for many days.

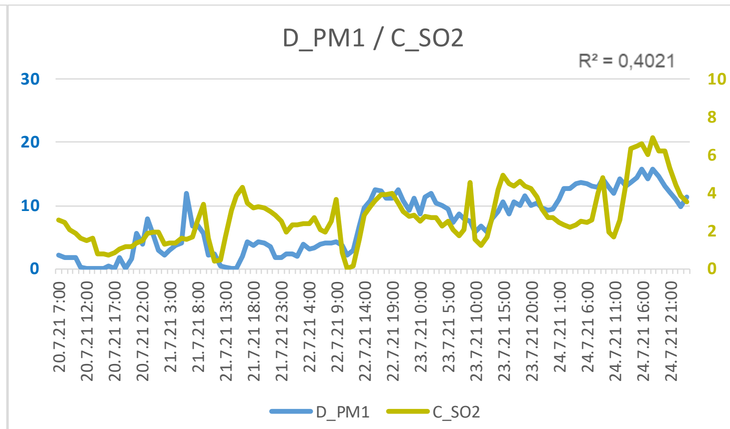


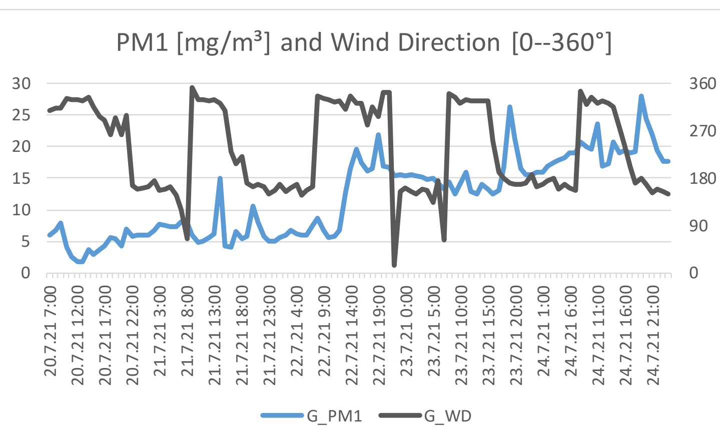


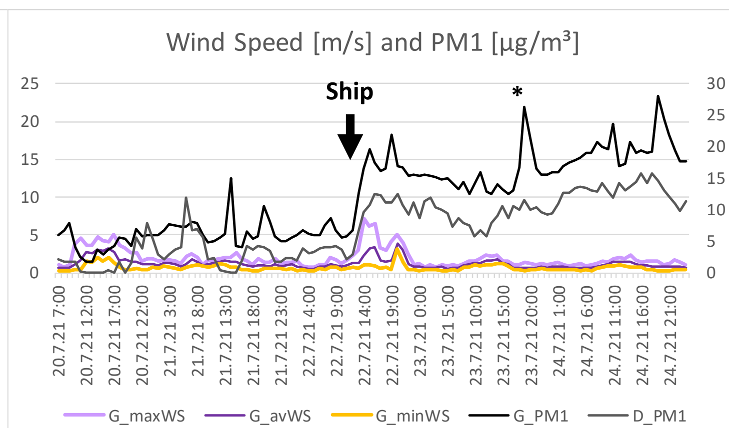












According to Hurtigruten Schedule 2021, *MS Richard With* left Bergen at 21st July, which visited Geiranger 22nd July 13:15—13:30 GMT+1.

* 23rd July: a small open fire was reported from the fjord

3.6 Results of Monitoring the Sound Levels

Our data cover the autumn and early winter period 2020 and the summer period 2021; we had a long period of missing data due to problems with power supply. As such, weather-driven phenomena of sound levels over different seasons cannot be shown here.

Sound levels at the dbC and dbA scale varied over the daily cycle under different weather conditions, but was far more constant during the report period than during the previous report periods.

dbA, as expected, showed different sound level patterns, in both, absolute values and temporal curves. Both, dbC (which incorporates a wider spectrum of sound) and dbA had a +/- constant daily minimum level over the example periods of 50 dbA and 45 dbC. These values should be seen as the reference.

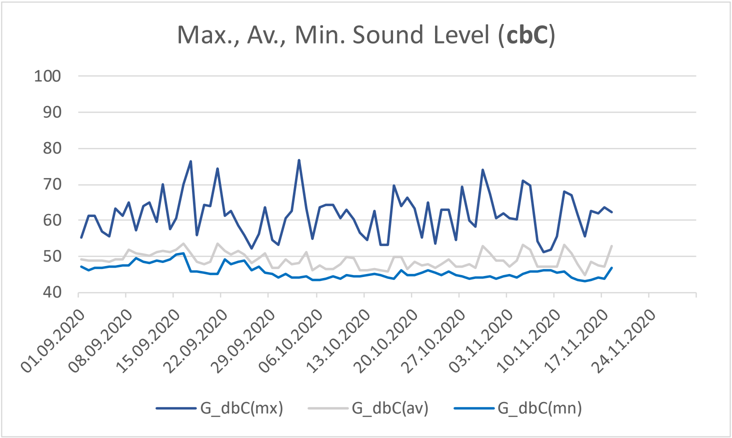
The comparison of sound levels from the report period with those from the previous year is critical. Different natural backgrounds do not allow to directly calculate the noise effect from traffic and business.

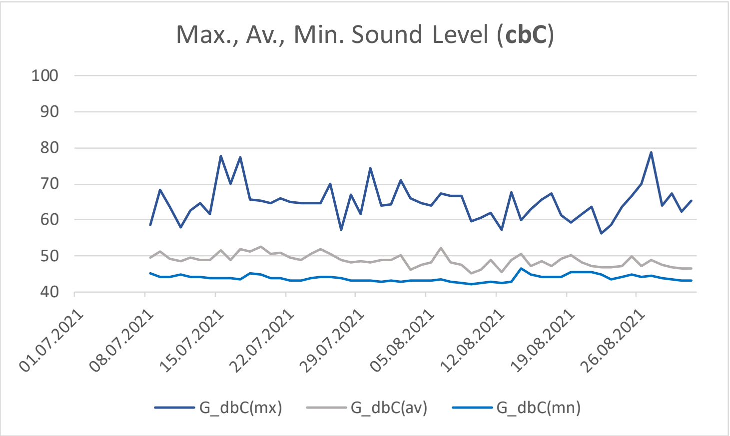
All in all, differences between natural and anthropogenic sound level signatures can be identified by comparing the minimum reference sound level per day with the daily maximum, when weather conditions were constant. Natural sound levels are best captured by low daily amplitudes of minimum and average data using week and months as reference interval.

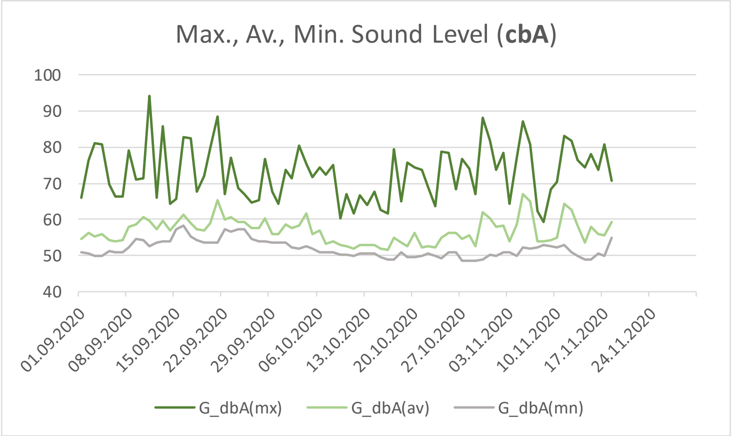
The data show very stabile sound levels during the summer 2021, which is in line with stabile weather conditions and low natural bias from "silent" waterfalls (early snow melt, little rain). Business hours are clearly expressed daily cycles in minimum sound levels, especially those of bdA, with added 10 to 15 db of the minimum sound level. The dbC sound level gives evidence of engines (cars, caravans, busses, ships, …), and our data show a slightly different pattern to that dbA, which covers the broader range of all sounds (incl. sound from individual people and crowds).

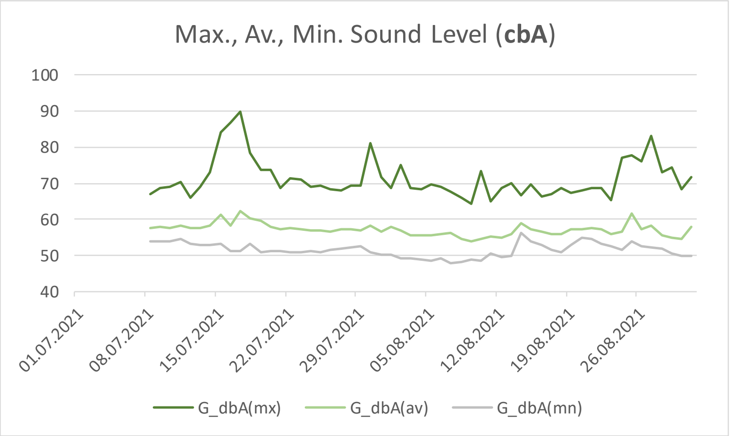
Overall, the new data should be seen as an experimental reference for the coming years, when different weather and traffic situations will be expected. Distinguishing between the different drivers of sound level patterns will very much be based on the two year of *Corona* situations.

Daily sound levels from two example periods

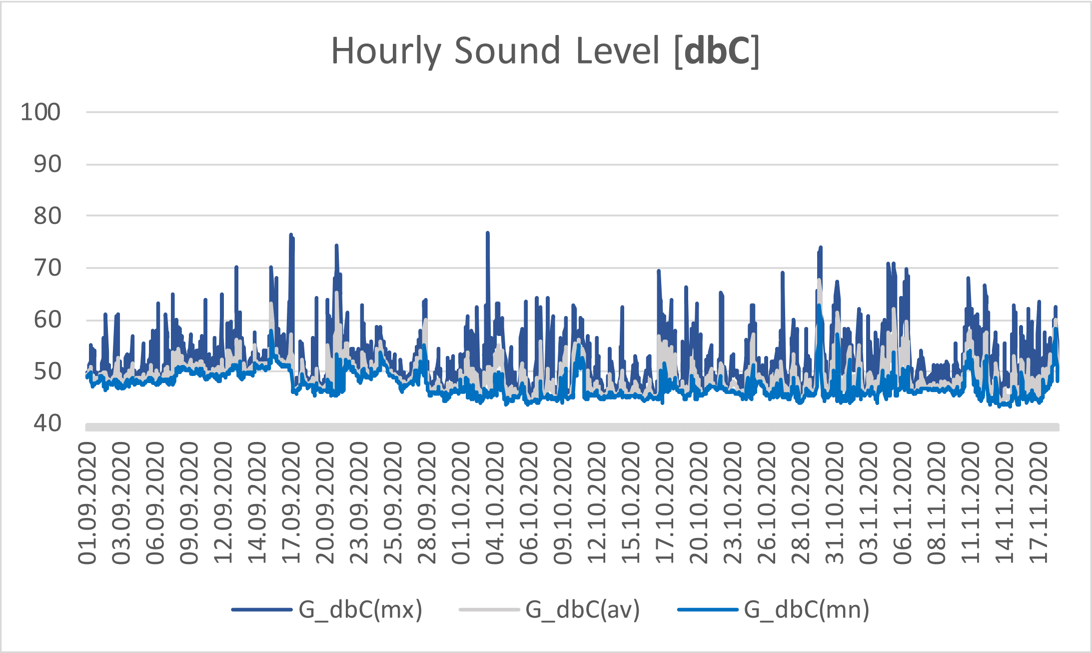


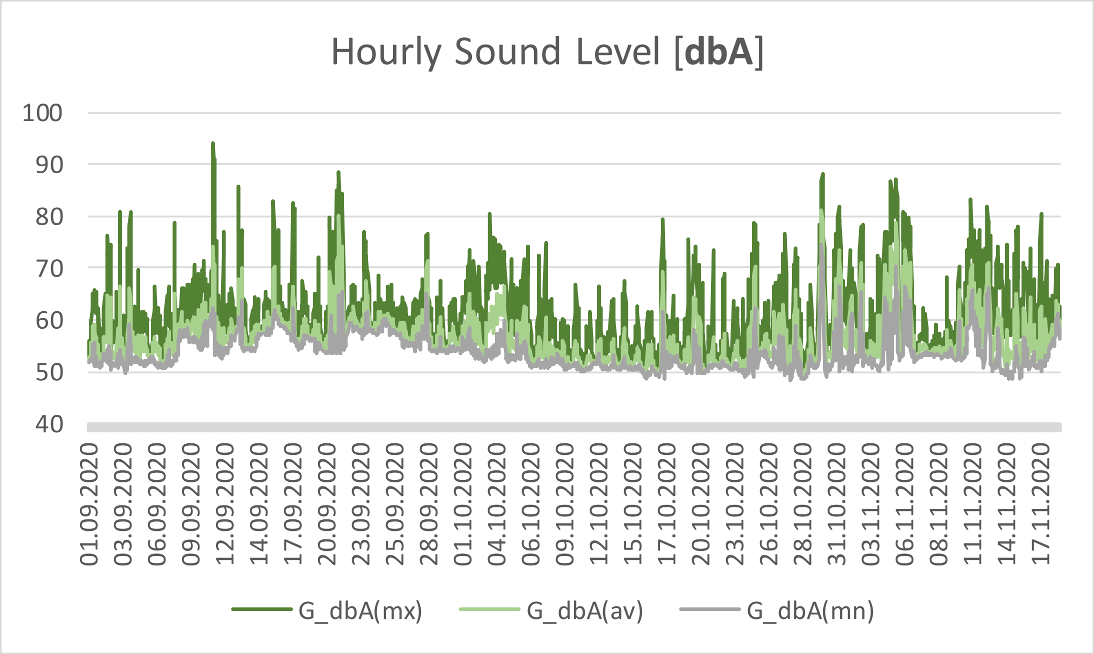




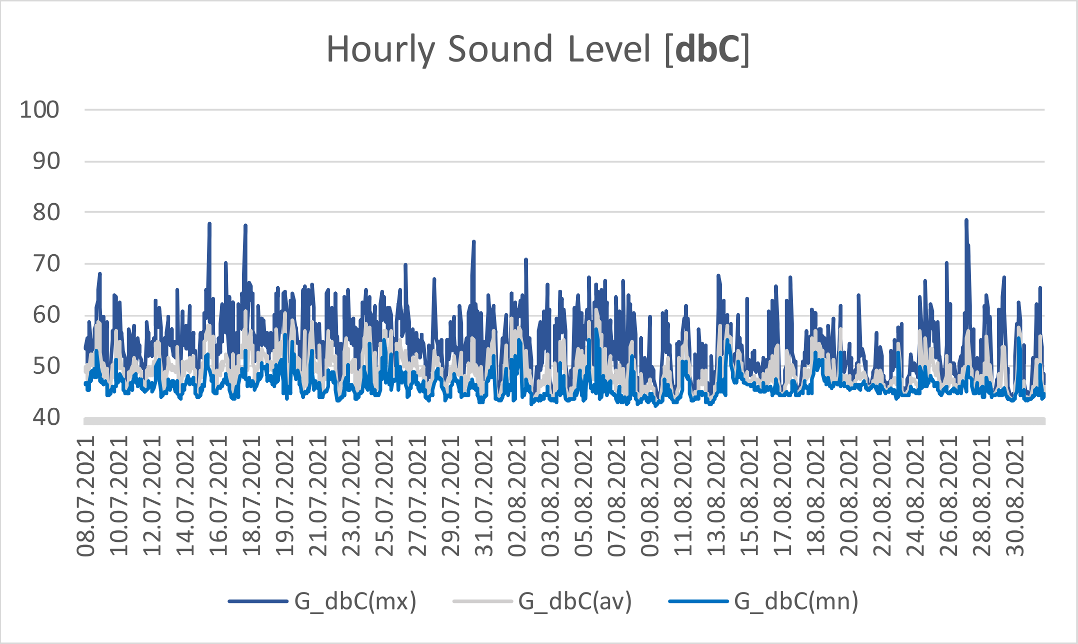


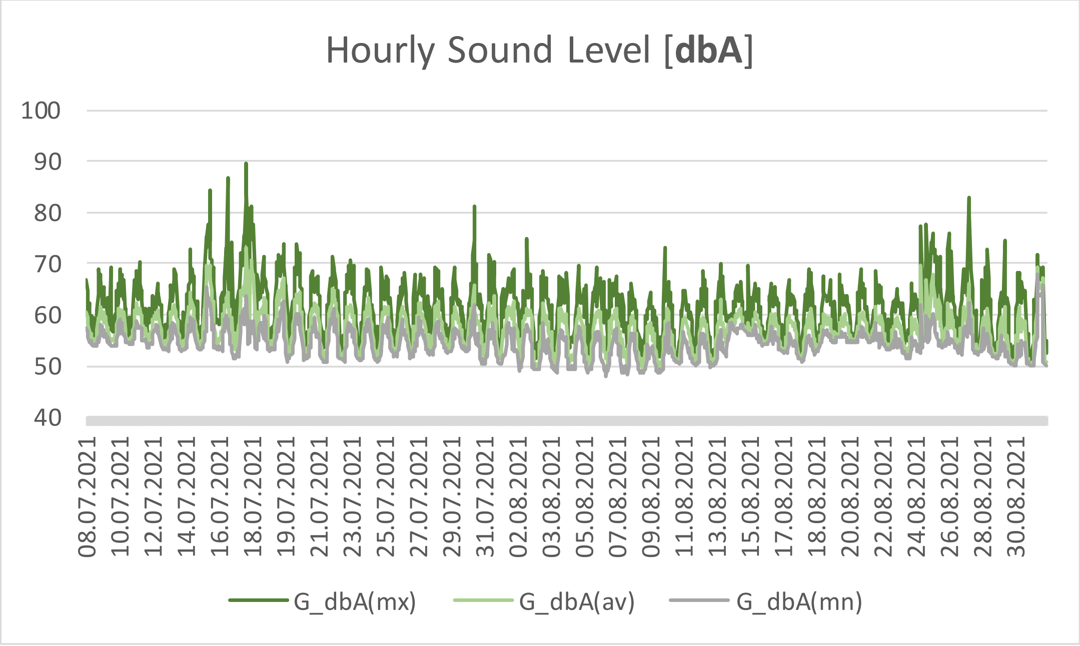
Hourly sound levels from autumn 2020





Hourly sound levels from summer 2021





4. Interpretation and Discussion

To interpret our findings it is necessary to keep in mind that we are talking about a very narrow and deep valley with complex topography and its unique mesoclimatic system.

Inversion layer at ~1100 m a.s.l., indicated by a 150 m thick cloud cover. High pressure weather situation 30.08.2021.

4.1 Year-to-Year Variability of Pollution Patterns

The variability of weather conditions especially in mountain areas is very high. This together with the variability of traffic with different sources of emissions and variable frequencies determines diverse pollution patterns.

The summer of 2015 had long periods of stable weather conditions which led to pronounced cumulative effects of PM concentrations in a small air volume of lower elevations. Unfortunately, data from higher elevation are not available from this year, but additional manual measurements had confirmed a stable and low lying inversion layer under which the dust was "trapped".

During the summer season of 2016 we were facing higher temperatures and higher air pressure, but also much higher variability of weather conditions. This meant that stabile atmospheric conditions were only short-term, and instability between these periods supported dilution of PM into a larger volume of air.

The summer of 2017 was even more turbulent and unstable than during the previous years, but also with lower temperatures, more cloud cover and very little impact of inversion weather conditions. Dilution of PM into the air was high, so that concentrations of PM were lower. As a consequence, pollution had in turn a much larger spatial extend even into the alpine areas.

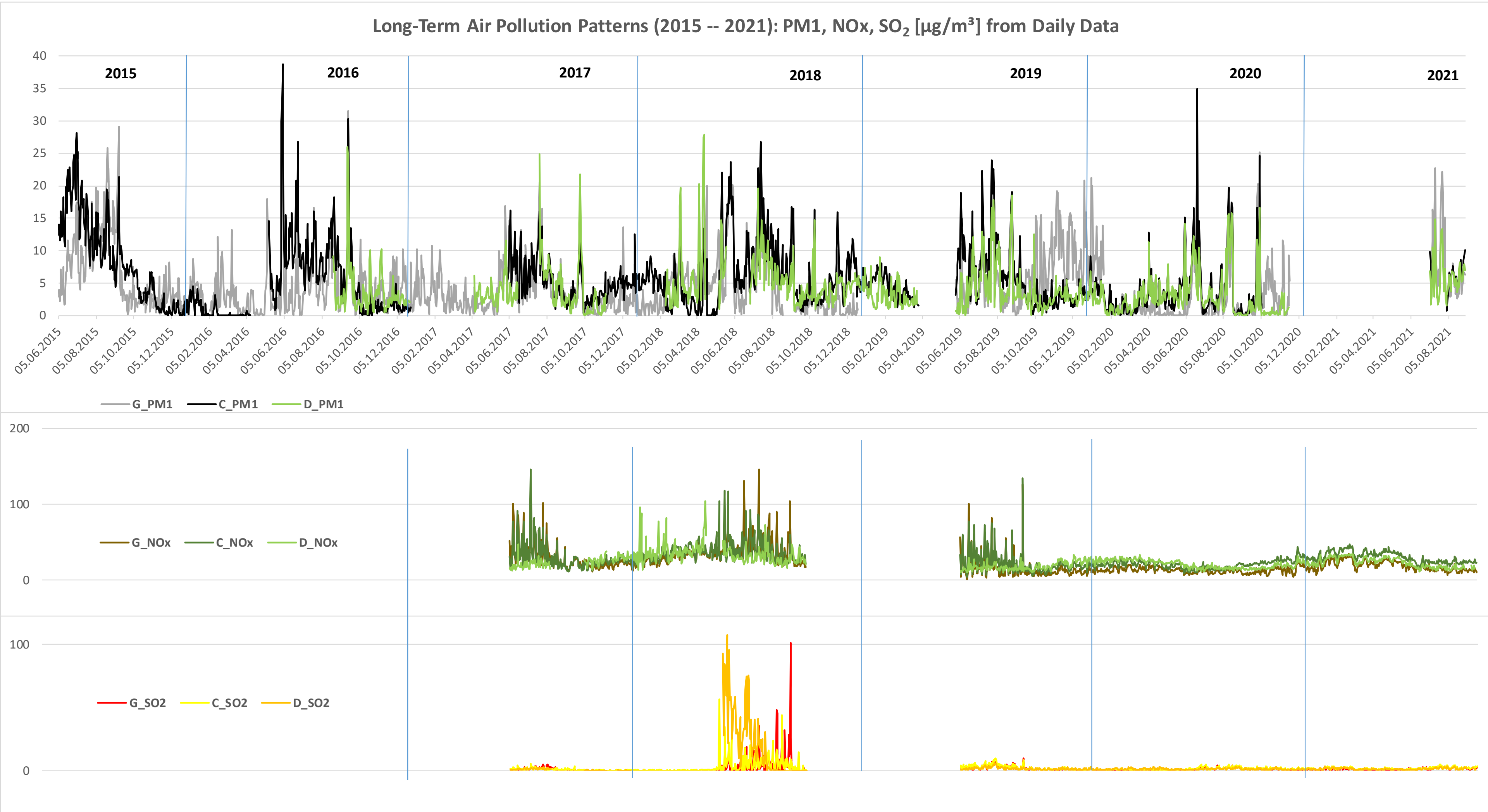
2018 was special: Due to a high pressure and very warm early spring period, which led to snow and ice melt early, a dry and hot early summer was accompanied with drought over weeks and high daily max. temperatures in July. Dilution during this period was driven by convective air, and as a result high PM concentration was found at higher elevation, trapped by an inversion layer. The late summer was driven by advective air streams from prevailing Westerlies, directed to southern (and eastern) components with strong foehn effect and resulting dilution of PM in to the entire volume of air in the valley.

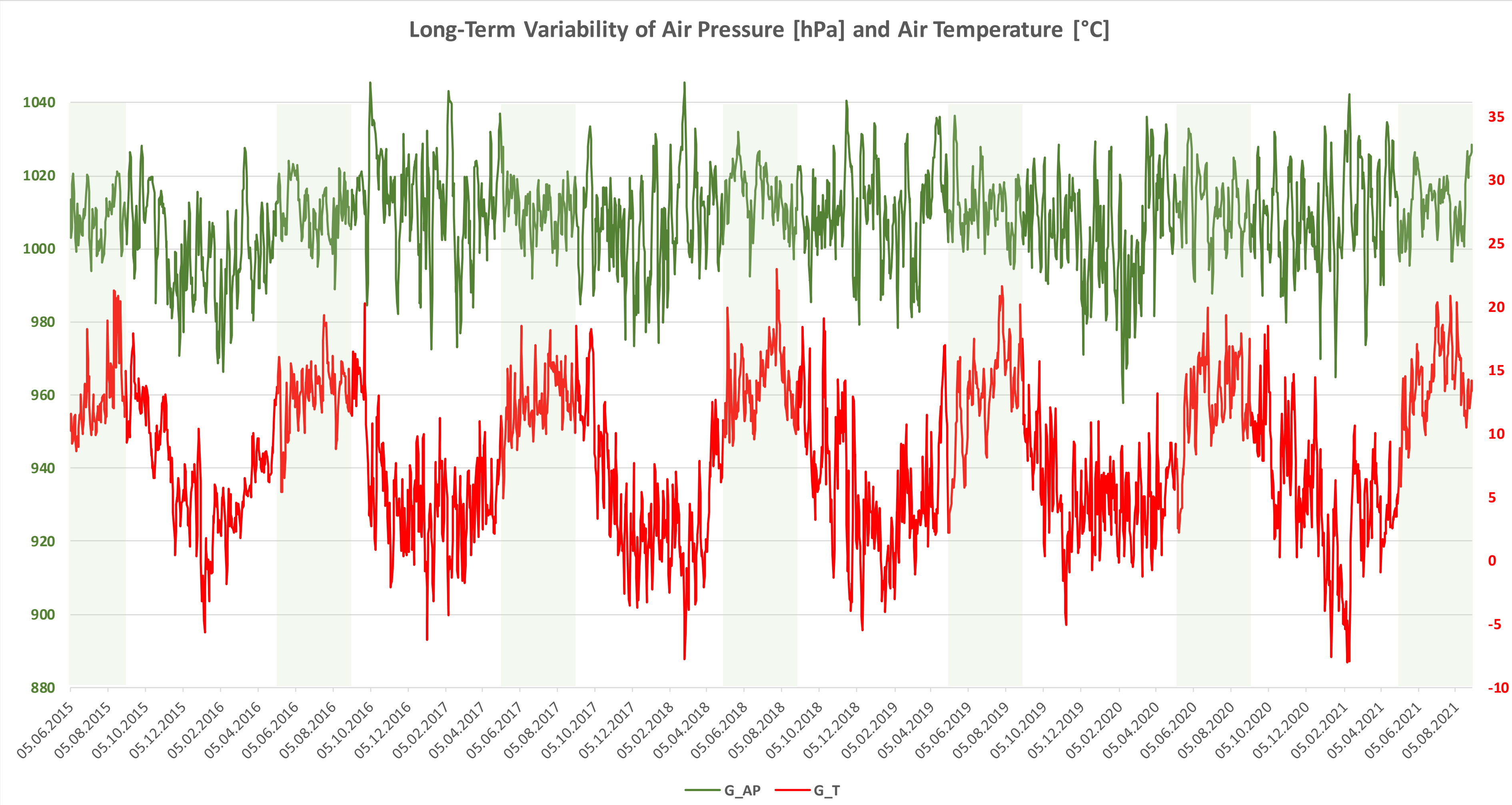
2019 was similarly turbulent like 2017, with short periods of stable weather. This might have mixed up the pollutants throughout the entire volume of air in the valley, leading to lower concentrations of particles at certain elevational levels , and consequently to generally higher concentrations with elevation. Still, data supporting this hypothesis are scarce!

2020 appeared as an unexpected experiment. The *Corona* pandemic situation did not allow cruise travels, and as a consequence sea traffic was very limit. It was a long and snow-rich winter, the connecting road to the south (F63) was closed until end of June, and the tourist season was restricted to July, mainly. As a result, July had very low concentrations of air pollutants, which was due to low emissions and weather. June and August both had single emissions from ships which turn into bad air quality especially also due to the weather.

2021 had similar pandemic restriction until the end of August, but weather conditions were much different than in 2020; after a cold winter with little snow, the summer was mainly dry and sunny. This in combination with long-lasting high air pressure resulted in ideal study conditions from which pollution patterns could be understood.

All in all, the results from the monitoring period 2015 -- 2021 show high variability of year-to-year pollution patterns.


Long-Term Air Pollution Patterns (2015 -- 2021): PM1, NOx, SO2 [µg/m³] from Daily Data
2015
2016
2017
2018
2019
2020
2021
G_PM1
C_PM1
D_PM1
G_NOx
C_NOx
D_NOx
G_SO2
C_SO2
D_SO2


Long-Term Variability of Air Pressure [hPa] and Air Temperature [°C]
1040
1020
1000
980
960
940
920
900
880
35
30
25
20
15
10
5
0
-5
-10
05.06.2015
05.08.2015
05.10.2015
05.12.2015
05.02.2016
05.04.2016
05.06.2016
05.08.2016
05.10.2016
05.12.2016
05.02.2017
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05.10.2019
05.12.2019
05.02.2020
05.04.2020
05.06.2020
05.08.2020
05.10.2020
05.12.2020
05.02.2021
05.04.2021
05.06.2021
05.08.2021
G_AP
G_T

4.2 Pollution Patterns and their Mechanistic Forces

Pollutions patterns in the Geiranger area again proved to be manifold from place to place, over the seasons, and in a year-to-year comparison. The mechanisms behind these patterns are manifold as well. But, in a general perspective on the entire valley the following conclusions can be drawn out of the results:

Air quality was poor during the previous years (2015—2019) compared to the size of the village, its remote position, the large intact natural mountain landscape, and to what is expected from a World Natural Heritage area. In earlier reports we compared the situation in the entire Geiranger valley with the air quality of a middle-sized European town (i.e. IHU & BGV 2016, LANUV 2016). During the last two years of pandemic restrictions (2020, 2021) the situation was changed, and far lower emissions were measured. But still, during single specific situations, better air quality quickly was reversed, e.g. by a single ship under specific weather conditions.

The smallest fractions of dust, namely PM_1 contribute by far the most to particulate fractions, of which a small proportion seems to remain trapped over longer periods (weeks) in the entire air volume of the valley. Moreover, the results from several winter periods suggest that they might even last for several months. This, together with the topography of the valley, results in a continuous cumulative phenomenon. Based on their specific combined dust fraction and gas signatures, single events from 2020 and 2021 give evidence of sources of emissions and residence times under certain weather conditions.

Once being exposed, PM_1 is suspended in the air and does not sediment by gravity. Weather driven decontamination of dust particles is limited, as can be conducted from our finding in the years 2020—2021 in particular. At least small proportions of PM1 are subject to cumulative effects according to their long residence times (e.g. Esmen & Corn 1971), which might even be underestimated.

Concentration of the PM and gaseous pollutants is a function of the capacity of the air volume involved. Under certain stable weather conditions (see summer of 2015), only a smaller volume in the lower valley atmosphere was part of the cumulative uptake of PM by the air. Consequently, higher concentrations were reached faster than under unstable conditions. Changing overall air pressure patterns, broad-scale turbulences, and cloudy weather which resulted in a) reduced local convective circulation, and b) reduced cold air flow from the mountains contributed to a much larger air volume being involved in the uptake and suspension of the pollutants. Exposure heat seems to be crucial for direct convective decontamination.

Esmen, N. A. & M. Corn (1971): Residence time of particles in urban air. Atm. Env. 5: 571-578.

IHU & BGV (2016): Stationsdaten-Altona-Elbhang. Hamburg. www.luft.hamburg.de (04.11.2016)

LANUV (2016): Jahreskenngrößen der Luftqualität in Nordrhein-Westfalen. (LANUV) Essen. https://www.lanuv.nrw.de/fileadmin/lanuv/luft/immissionen/ber_trend/Disko-Immissionen-2015-PMx-1.0.pdf, (27.09.16)

5. Conclusions

During the report period we again measured high concentrations of the finest fractions of particulate matter as the major pollutants. These dust particles (PM_1) most likely originate mainly from diesel engine exhausts, and they appear together with a specific very fine signature of SO_2. The timing of emissions which are brought into the area (i.e. how much dust is produced at a certain day) was found to be of minor importance. It was rather that one single event of emissions under certain weather conditions might lead to high concentrations in a small air volume of the narrow valley. Together with a residence time of weeks and months, a smaller proportion of emissions might be trapped in a cold and turbulent air volume, from which decontamination is limited.

Separating the various explanatory variables helped to explain certain conditions of pollution. To understand the entire system under different weather and traffic conditions, a complex approach is required. There are numerous scientific activities which are based on the data from this monitoring program, all of which serve as parts of a big puzzle. Currently, there is no final result to be reported, and there is not one simple story to be told.

The situation is complex. Pollution can be temporarily high, even if the total amount of emissions is limited (like in 2020 and 2021). Impact of different types of sources contribute to air quality in the area. Weather conditions modulate the concentration of emissions, but as the diversity of weather situations and the variability of their impact on air quality is high, single weather variables act and interact in complex ways, so that the strength of single drivers remains quite low throughout longer time series.

Despite a long period of missing data on PM, 2021 together with the previous year offered perfect study conditions, especially due to long periods of high pressure summer weather. The re-start of cruise traffic at the end of this report period is scientifically most promising to further study residence times of air pollutants in the unique topography.

Contact

Prof. Dr. Jörg Löffler
Department of Geography, University of Bonn
Meckenheimer Allee 166, D-53115 Bonn, Germany
Phone: +49 228 73 7239, Fax: +49 228 73 7506, Mobile: +49 178 5528984
Email: joerg.loeffler@uni-bonn.de
http://www.geographie.uni-bonn.de/forschung/arbeitsgruppe-loeffler