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# EMISSIONS TO AIR AND DISCHARGES TO SEA FROM SHIPS IN FJORD AREAS WITH HEAVY CRUISE TRAFFIC

## MAPPING AND PROPOSED MEASURES


RAMBOLL

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## SUMMARY

Rambøll was commissioned to map emissions to air and discharges to sea from ships for the summer season May to September (June to August for parts of the work) of 2016 by carrying out various activities. The world heritage fjords the Geirangerfjord, the Aurlandsfjord in to Flåm and the Nærøyfjord were prioritised, as these fjords have the heaviest cruise ship traffic.

A questionnaire was prepared by SINTEF MARINTEK and distributed to ships that visited the three fjords during the summer of 2016. The survey collected information about the ships' technical data and their operational profile when proceeding in the fjord areas. In Geiranger, a video camera was installed that monitored the Geirangerfjord during parts of the 2016 cruise season. Modelling of meteorological conditions in the three fjords was carried out by using the Weather Research and Forecast Model (WRF), which was in turn used as input data for the dispersion modelling. Emissions of nitrogen oxides ($NO_x$) were estimated for all vessels that visited the world heritage fjords during the summer months June to August 2016 by using data from the questionnaire. For ships registered as cruise or passenger ships, the emissions of $NO_x$, sulphur dioxide ($SO_2$) and particulate matter ($PM_{10}$ and $PM_{2.5}$) were estimated using actual data on ship movements and available technical data on individual ships from ship databases. Emissions from road traffic in the areas were also estimated based on available traffic numbers and emission factors. Dispersion calculations for sulphur dioxide ($SO_2$), nitrogen dioxide ($NO_2$), $PM_{10}$ and $PM_{2.5}$ were performed for the period from June to August 2016 with the modelling system CALPUFF, with modelled meteorology for the areas and estimated emissions from the cruise and passenger ships used as input data.

Photos of the ship traffic in the Geirangerfjord taken with the video camera showed formation of clearly visible smoke clouds both from cruise and passenger ships and from other vessels. White smoke mainly consists of condensed water vapour, whereas grey/black or blueish colour indicates emission of soot/particles and unburned hydrocarbons.

Around half of the vessels responded to the questionnaire. The data on the cruise ships are considered as representative since the age distribution of the ships from which we received responses, does not deviate significantly from the age distribution of the global cruise ship fleet.

The calculations showed that the emissions were clearly the largest for $NO_x$ in the period from June to August 2016, and the highest in the innermost parts of the Geirangerfjord and in the Aurlandsfjord near Flåm. The cruise and passenger ships contributed the most to the $NO_x$ emissions: 81% of the total emissions in the Geirangerfjord and 84% in the Aurlandsfjord and Nærøyfjord. Other vessels contributed with between 9 and 17%, and the road traffic on land with only around 2 and 7% of the total emissions.

The CALPUFF dispersion calculations show that it was principally concentrations of $NO_x$ that from time to time were elevated. The levels of $PM_{10}$, $PM_{2.5}$ and $SO_2$ were for the most part low, with values below the applicable action limit values pursuant to the Pollution Regulations. For $NO_2$, the levels were below the hourly limit value of 200 $\mu g/m^3$ most places. The limit value was exceeded over short periods of time in small, uninhabited areas in the fjord and in one mountainside; only small areas had $NO_2$ concentrations just below the hourly limit value.

The alert classes drawn up by the Norwegian Institute of Health, the Norwegian Public Roads Administration and the Norwegian Environment Agency are used to indicate air quality in cities in relation to health risk, and have hourly mean limits for all the mapped components. In periods, large areas around the Geirangerfjord in the innermost part of the Aurlandsfjord near Flåm had $NO_2$ concentrations that fell into the alert class for moderate level of pollution and health risk, which has a lower limit of 100 µg/m$^3$, i.e. under the limit value pursuant to the Pollution Regulations. The survey thus indicates that the levels of $NO_2$ in the areas in the innermost parts of the Geirangerfjord and in the Aurlandsfjord near Flåm are periodically so high that they could lead to aggravation of disease in vulnerable population groups.

The $PM_{10}$ levels did not exceed any of the alert class limits at any point in any of the world heritage areas, whereas concentrations of $SO_2$ and $PM_{2.5}$ exceeded the lower limit for moderate level of pollution and health risk in short periods of time in small, uninhabited areas in the fjord and in one mountainside.

Based on the results from the mapping of emissions and discharges from ships in the world heritage fjords, possible measures for reducing the pollution and smoke formation were considered. Measures directed at introduction of stricter requirements for emissions and discharges and for technology on board the ships calling at the fjord areas may potentially be implemented. The most extreme consequence could be laying down restrictions in the number of ships allowed to visit the areas or granted port call permissions. Setting up shore power facilities could also be a solution in several ports. It is also possible to extend the existing emission control area in the North Sea to include more fjord areas further north in Norway. Implementation of this type of measures will involve a number of economic and legal challenges, and many factors must be taken into account. Measures that are a part of national and international requirements could possibly be sufficient.

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# 1. INTRODUCTION

## 1.1 Background

In Norway, some fjords experience heavy cruise traffic, particularly in the three summer months of June, July and August. The world heritage sites the Aurlandsfjord in to Flåm and the Geirangerfjord have the most traffic, but other fjords also have a considerable amount of ship traffic.

In areas with heavy ship traffic, the shipping activities may generate significant amounts of discharge and emissions. The cruise ships are large, and are often moored with the auxiliary engines running overnight, sometimes even with the main engine running. This generates or could generate emissions of water vapour, sulphur dioxide ($SO_2$), nitrogen oxides ($NO_x$), carbon dioxide ($CO_2$), particulate matter ($PM_{10}$ and $PM_{2.5}$) and unburned hydrocarbons (UHCs). Some of these substances may be detrimental to health in concentrations above a certain level. Legally binding action limit values are set out in chapter 7 of the Pollution Regulations, whereas air quality criteria used to assess air quality in city areas may be used to assess level of pollution and health risk for the air pollutants in question for shorter periods of time. Smaller ships such as ferries and high-speed craft have the same kinds of emissions, but only contribute a small part of the overall emissions in the largest cruise fjords. The authorities therefore wanted to identify relations between cruise traffic and other ship traffic and to map concentrations of substances that are potentially detrimental to health, compared to air quality criteria and/or applicable limit values.

From time to time, on days with little wind, a smoke cloud can be observed above the ships and the fjord areas, which constitutes a form of visual pollution that should be reduced as much as possible. A mapping of the extent of the formation and the content of such smoke clouds was needed, and of whether such episodes are connected with health risks.

Cruise ships and other ship traffic also discharge substances into the sea. Either sewage must be treated before discharged into the sea, or it must be discharged at a certain distance from land. All ships are allowed to discharge so-called "grey water", i.e. wash water. Other types of discharge to sea are also an issue, such as discharge of ballast water, undesirable organisms, oily substances, anti-fouling coatings and garbage. The authorities wanted to look into the scope of discharges to sea and which types of discharge occur in connection with shipping in the world heritage fjords.

Based on this, the NMA wanted to carry out a mapping of discharges from vessels in the fjord areas in question during the summer season of 2016 in order to evaluate risks of possible health effects and harmful impacts on the natural environment in these areas. The world heritage fjords the Geirangerfjord, the Aurlandsfjord in to Flåm and the Nærøyfjord were given priority.

## 1.2 The goal of the project

The following goals were set for the project:

1. To map emissions to air and discharges to sea in the Geirangerfjord, Aurlandsfjord and Nærøyfjord in the summer months
2. To propose measures that can reduce emissions to air and discharges to sea from ships in the relevant fjord areas

## 1.3 Activities and analyses

In the study, emissions to air and discharges to sea from ships in the selected fjord areas were mapped by carrying out a survey directed at relevant shipping companies, cruise ships and local ship traffic including Hurtigruten, video monitoring of the ship traffic in the Geirangerfjord, and estimation of emissions and modelling of the dispersion of relevant polluting components from the cruise ship traffic.

### 1.3.1 Survey

Data from ships sailing in fjord areas in Norway were collected by way of a questionnaire. The questionnaire included questions on the ships' technical data, operational profile and conditions relevant for emissions to air and discharges to sea, and was distributed to the cruise ships and the local ships that visited the Geirangerfjord, Aurlandsfjord and Nærøyfjord during the months from May to September 2016. SINTEF MARINTEK conducted the survey. The results from the survey were used as input data for the modelling of the dispersion of air pollution emitted from cruise ships in the fjord areas in question.

### 1.3.2 Video monitoring

Pictures were taken at regular intervals with a camera mounted overlooking the Geirangerfjord in parts of the 2016 cruise season. By using these pictures, the ships' movements over time could be tracked, and emissions from ships resulting in visible smoke clouds could be observed. The photo series could also be used for verification of ship movement data, and for evaluating calculations of air pollution emissions and dispersion out into the fjord areas.

### 1.3.3 Meteorological modelling

A meteorological modelling was carried out for the summer months of June, July and August 2016 for use in the modelling of air quality in the selected Norwegian fjord areas. The simulated meteorological data were used to assess the dispersion of the relevant polluting components in air emitted by cruise ships. Meteorological information is necessary in the modelling of air quality, since parameters such as wind speed, temperature and humidity affect how polluting components disperse and react in the atmosphere. Existing sources of meteorological information include data sets with measurements taken at various locations by existing meteorological stations at the fjord areas along the west coast of Norway. However, the number of measuring stations close to the fjord areas in this study was not sufficient to describe the three-dimensional structure in the atmosphere with a high enough degree of accuracy.

When using measuring results from meteorological stations as input data, grid-based meteorological models can estimate meteorological conditions in areas far from the measuring points. The results from these models are often used to determine conditions in places that are either close to or downwind from sources of pollution. The Weather Research and Forecasting (WRF) Model is currently the preferred mesoscale model (approx. five to several hundred kilometres) for atmospheric research and operational forecasting. WRF was chosen and used to generate meteorological input data for the modelling of dispersion of emissions from cruise ships in the Geirangerfjord, Aurlandsfjord and Nærøyfjord for the summer months of June, July and August 2016 at 300-metre horizontal resolution.

### 1.3.4 Estimation of emissions from ships

Emissions from all ships that called at the Geirangerfjord, Aurlandsfjord and Nærøyfjord during the period from June to August 2016 were estimated based on the technical ship data from the questionnaire and established emission factors. For the cruise ships, the emissions were estimated more precisely by using data for actual ship movements and information about each vessel. The emissions were calculated by relating individual vessels to engine parameter data in order to estimate engine load, and by using emission factors and AIS ship movements for the summer of 2016.

AIS is an automatic identification system for tracking ship traffic. All ships equipped with AIS transceivers broadcast their position, speed and course with short regular intervals through the ship's identification number or IMO or MMSI (Maritime Mobile Service Identity) number. The ships and their AIS data can thereafter be compared to information about ship type, year of construction, size, dimensioning speed, engine properties and other information in order to estimate engine load and emission factors through using data from the IHS Fairplay database.

### 1.3.5 Dispersion modelling

Estimated emissions from ships calculated by using AIS data were entered into the CALPUFF modelling system in order to estimate the impact on local air quality in the Geirangerfjord, Aurlandsfjord and Nærøyfjord. CALPUFF was chosen as dispersion model, since this system can take complex three-dimensional wind conditions into account. The dispersion of the air pollutants nitrogen dioxide ($NO_2$), sulphur dioxide ($SO_2$) and particulate matter ($PM_{10}$ and $PM_{2.5}$) in the three fjord areas was estimated and assessed against applicable regulations and limit values.

The modelling results were validated against ongoing measurements in the Geirangerfjord. Several meteorological parameters and relevant air pollutants are measured as part of a long-term project headed by Professor Jörg Löffler at the University of Bonn in Germany and financed by the foundation Stiftinga Geiranger Verdsarv. Rambøll established a cooperation with Professor Löffler and Katrin Blomvik, general manager of Stiftinga Geiranger Verdsarv, in connection with the execution of this survey so that measuring data and results could be exchanged for the purpose of validation. The results from measurements of $SO_2$ and particulate matter in the air around the port area of Geiranger were compared to modelled concentrations of the same components. Access to results from both dispersion modelling and measurements provides varied, but supplementing information for evaluation of the air quality in an area.

### 1.3.6 Proposed measures

Based on the mapping of emissions to air from ships in the three fjords through a survey, video monitoring, estimation of emissions and dispersion modelling, possible measures were proposed. The results from the current survey were also compared to previous surveys conducted in fjord areas in Norway.

# 2. GENERAL INFORMATION ABOUT SHIPPING AND POLLUTION

## 2.1 Pollution from shipping and potential effects

Shipping causes significant amounts of emissions to air and discharges to sea, and can contribute to poor air quality locally and harmful effects on ecosystems in the sea, particularly in larger port areas.

### 2.1.1 Emissions to air

The ship machinery consists of the main engines that provide the vessel's propulsion, and the auxiliary engines that are used to power functions on board not related to the propulsion, such as electricity for lighting, heating and similar. Marine diesel engines normally run on sulphurous heavy fuel oil, whereas start-up and manoeuvring takes place using marine diesel oil.

Exhaust gases from ships mainly consist of carbon dioxide ($CO_2$), water vapour, nitrogen oxides ($NO_x$), sulphur oxides ($SO_x$), particulate matter (PM), carbon monoxide (CO) and volatile organic compounds (VOC), including unburned hydrocarbons (UHC), [1] see illustration and explanation in Figure 1.

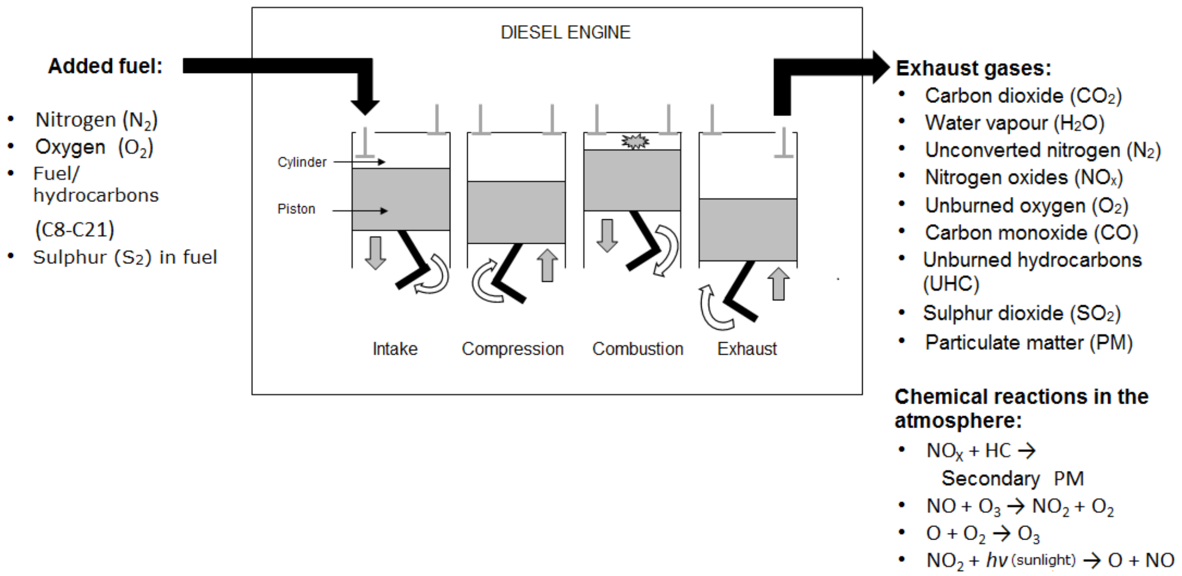


**Figure 1. Illustration showing a schematic presentation of the manner of operation of a marine diesel engine, and an overview of added fuel, exhaust gases and atmospheric chemistry.**

**In a combustion engine, the fuel's energy content is converted to mechanical power by combustion inside the engine's combustion chamber. The thermal energy liberated during the combustion pushes down a piston. Diesel engines have a high compression pressure in the combustion chamber, and a temperature that is so high that the fuel self-ignites upon intake. Clean air is fed to the cylinders. The combustion leads to an expansion, which pushes the piston downwards.**

**The exhaust gases released to the air consist of products of combustion, mainly carbon dioxide ($CO_2$) and water vapour ($H_2O$). The most important pollutants with regard to local air quality are nitrogen oxides ($NO_x$), sulphur dioxide ($SO_2$), particulate matter (PM), carbon monoxide (CO) and unburned hydrocarbons (UHC). Some of the compounds in the exhaust gases form part of a number of chemical reactions in the atmosphere. $NO_x$ and hydrocarbons form secondary particulate matter. Nitrogen monoxide (NO) and nitrogen dioxide ($NO_2$) form part of a cyclic process where ozone ($O_3$) is central, and this equilibrium varies depending on atmospheric conditions such as irradiance and ozone concentration.**

Various pollutants released to the air may have negative effects on the earth's climate, ecosystems and human health. Emissions of greenhouse gases such as carbon dioxide ($CO_2$) from shipping and contributions to global warming are not covered by this report. Harmful effects on ecosystems in the sea and on land will be mentioned, but the main emphasis will be on concentrations of relevant air pollutants and potential harmful effects on people living and staying in the world heritage fjords with heavy cruise traffic.

Air pollution is one of the most important causes of premature death and damage to health on a global scale, and harmful effects have been established at low concentrations in air.[2] Nitrogen oxide ($NO_2$), particulate matter ($PM_{10}$ and $PM_{2.5}$) and sulphur dioxide ($SO_2$) are considered the most important pollutants in air in areas with a high percentage of ship traffic. This is based on the size of the emissions, typical concentrations in the atmosphere and potential damage to health.[3] These components have therefore been examined more closely in this report.

Nitrogen dioxide

Nitrogen oxides ($NO_x$) are formed by combustion of fuel at high temperatures. Marine diesel engines in particular have a high level of $NO_x$ emissions. The actual emissions mainly consist of nitrogen monoxide (NO) and smaller amounts of nitrogen dioxide ($NO_2$). In addition to depending on the type of fuel, the percentage of $NO_2$ in ambient air will also depend on atmospheric conditions, as NO can oxidise in air to nitrogen dioxide ($NO_2$) in the presence of ozone ($O_3$). Furthermore, NO can be reformed from $NO_2$ by absorption of energy from sunlight. The free oxygen atoms (O) formed thereof react with oxygen in the atmosphere to form ozone. $NO_x$ compounds also form part of a number of other chemical reactions in the atmosphere. Conditions such as irradiance, precipitation, ozone concentration and distance to the source of emission will therefore be decisive for the distribution between NO and $NO_2$ in the air in various areas and at various times.

$NO_2$ is the most relevant compound to consider when it comes to health damage in humans.[4] Limit values for human health have therefore been laid down for the component $NO_2$.

Particulate matter (PM)

Airborne particulate matter has a very complex and varying composition, and forms part of a number of chemical reactions and physical processes in the atmosphere.[5] The source of particulate matter may be both natural and anthropogenic. The burning of fossil fuels is one of the most significant sources of emission. Road traffic on land will also contribute to the emission of particulate matter, both in the form of combustion particles in exhaust gases from vehicles and by dust being stirred up into the air through wear of brake pads, tires and asphalt.

Particulate matter may divided into size fractions based on the size of the particles. Commonly used size fractions when evaluating outdoor air quality include particles with diameters smaller than 10 µm, 2.5 µm and 1 µm ($PM_{10}$, $PM_{2.5}$ and $PM_1$), and particles with a diameter of less than 0.1 µm, or ultrafine particles ($PM_{0.1}$). The coarse particle fraction ($PM_{2.5-10}$) of particulate matter in city air mainly comes from road surface wear, whereas the fine ($PM_{0.1-2.5}$) and ultrafine fractions mostly originate from combustion. Particle size is considered a decisive factor for potential adverse effects of particulate matter on health. Studies indicate that $PM_{10}$ is mainly associated with effects on the pulmonary system, whereas $PM_{2.5}$ is associated with adverse effects on the cardiovascular system.

Sulphur dioxide

Pollution by sulphur dioxide can lead to adverse health effects, particularly aggravation of diseases and increased mortality in asthmatics.[6] The effect of inhalation of $SO_2$ is mainly constriction of the airways, and thus reduced lung function. However, the concentration of $SO_2$ in the air must be relatively high in order to produce such effects. The emissions and concentrations in outdoor air of $SO_2$ have been considerably reduced in the Western world over the last decades, and $SO_2$ therefore does not pose a health risk most places in Norway.

Emissions from ships from the combustion of sulphurous fuel have been a significant contribution to the total emissions of sulphur oxides ($SO_x$) in Europe.[7] However, new emission requirements have contributed to reducing these emissions. This particularly applies within emission control areas defined by IMO (ECAs) and for operation in ports, where ships are currently using fuels with low sulphur content or pollution-reducing technology in order to satisfy the emission requirements.

### 2.1.2 Discharges to sea

Discharges into the sea from shipping could lead to considerable harmful effects on marine ecosystems.[8] Relevant discharge types include sewage, grey water, ballast water, oily compounds, anti-fouling coatings and garbage.

Cruise ships are equipped with sewage treatment/cleaning systems in accordance with applicable requirements in order to minimise health risks and damage to the environment from sewage. Such systems shall prevent discharge of harmful substances such as coliform bacteria and shall prevent visible particles from being discharged. There are technical requirements for biochemical oxygen demand related to nitrification in the treatment process and requirements for pH content of discharged water. A requirement has furthermore been set for nitrogen and phosphorous content that may be discharged in order to avoid supplying nutrient salts that could lead to increased plant production and algae bloom in the sea. Smaller ships such as ferries and fjord cruise boats normally have simpler sewage systems.

Grey water can be treated specially or be connected to the sewage systems on board. Ballast water shall be managed in accordance with the Ballast Water Regulations that lay down requirements for how exchange and management of ballast water is to take place. It is normally not allowed to exchange ballast water in Norwegian fjords.

Anti-fouling coatings are applied to ship hulls in order to prevent biofouling, so that the hull is kept as smooth as possible to minimise resistance in water and so that the ship can maintain desired speed with the lowest possible fuel consumption. It is currently prohibited to use toxic anti-fouling coatings that could affect marine organisms.

There are requirements for discharge of bilge water, and this shall contain no more than 15 ppm oil.

## 2.2 Regulations and limit values

### 2.2.1 Emissions to air

The following section contains a detailed presentation of relevant international conventions and national laws, regulations, guidelines and non-legal limits related to emissions to air and discharges to sea from shipping and local air quality.

Emissions to air from shipping are regulated through the international MARPOL Convention Annex VI.[9] Other applicable international agreements and regulations are Directive (EU) 2005/33/EC[10], that is related to the sulphur content of marine fuel, and the Gothenburg protocol, that includes emissions inter alia of $SO_x$ and $NO_x$. The requirements for local air quality are laid down in chapter 7 of the Pollution Regulations[11], that are for the most part in accordance with EU's Air Quality Directive[12]. Guidelines have additionally been prepared (T-1520), which are used in area planning and include zone limits for air pollution.[13] The Norwegian Institute of Health has moreover drawn up air quality criteria for a number of air components.[14] The website luftkvalitet.info operates with alert classes for shorter periods of time for certain components.[15] For the smallest particles, the size fractions $PM_1$ and $PM_{0.1}$, there are no limit values.

The results from the dispersion calculations have been assessed against the action limit values in chapter 7 of the Pollution Regulations, and the air quality criteria are given as hourly levels.

MARPOL, Annex VI

The International Convention for the Prevention of Pollution from Ships (MARPOL) was implemented by the UN's international maritime organization (IMO) in 1973[9], and applies as regulation in Norway (Regulation on environmental safety for ships and mobile offshore units, the Ministry of Climate and Environment, 2012)[16]. Emissions to air from shipping are regulated by MARPOL Annex VI on the prevention of air pollution from ships. Annex VI was adopted in 1997, and a revision was implemented in 2010.

The Convention contains detailed provisions on e.g. control of emission of $NO_x$, $SO_x$, particulate matter, VOC and ozone-depleting substances, shipboard incineration of waste, repairs and fuel oil quality.

MARPOL defines specific emission control areas (ECAs) where special requirements apply for the emission of $SO_x$ and $NO_x$. The ECAs comprise the coast along North America, the Baltic Sea, the English Channel and parts of the North Sea up to 62°N.

The requirements in MARPOL that apply to the emission of $NO_x$ are referred to as Tier I, Tier II and Tier III standards. The emission requirements are related to maximum rated engine speed on the vessels. The Tier I requirements apply to ships constructed after the year of 2000, while the stricter Tier II limits apply to ships constructed after 2011. In ECAs, the Tier III requirements apply to ships constructed after 2016.

EU Directive 2005/33/EC

EU Directive 2005/33/EC, adopted in the EU in 2012 and incorporated into the EEA Agreement in 2014, sets requirements for sulphur content of fuel for ships in the EU, so that these are in compliance with the MARPOL requirements.[10] The limit for marine fuel used in the EU/EEA is 3.5% in accordance with the global limit, from 2020 it will be 0.5%. In the ECAs, the limit is 0.1%, applicable from 2015. For marine gas oil, the limit is 0.1% in all areas. For the EU, two special rules apply: a limit of 0.1% applies to ships at berth or anchor in a port area, and a limit of 1.5% applies to passenger ships on a regular service within or to and from the EU/EEA.

The Gothenburg protocol

The Gothenburg protocol was adopted in 1999, entered into force in 2005 and was revised in 2012, and has been ratified by most countries in Europe, the USA and some Asian states.[17] The protocol includes requirements related to emissions of pollutants that lead to acidification, eutrophication, ozone formation and particle formation, and thus comprises $SO_x$, $NO_x$ and certain volatile organic compounds. The countries that have ratified the protocol have committed to certain percent-wise emission reductions of the relevant compounds. For instance, Norway has committed to reducing the emissions of $SO_2$ and $NO_2$ by 10% and 23% respectively, in relation to the base year 2005.

EU's Air Quality Directive

Directive 2008/50/EC of the European Parliament and of the Council on ambient air quality and cleaner air for Europe (EU's Air Quality Directive) regulates the components $SO_2$, NO, $NO_2$, particulate matter ($PM_{10}$ and $PM_{2.5}$), lead, benzene, CO and ground-level ozone, and includes provisions on and requirements for reporting of action plans, monitoring programs and quality assurance of air quality assessments.[12] The Directive was adopted in 2018, and is also incorporated into the Norwegian Pollution Regulations. The limit values set out in Annexes XI and XIV to the Air Quality Directive are thus concurrent with the action limit values set out in section 7-6 of the Pollution Regulations, except for the limit values for $PM_{2.5}$ where Norway has introduced stricter requirements: The annual limit value for $PM_{2.5}$ was in Norway reduced to 15 µg/$m^3$ applicable from 1 January 2016, compared to the annual limit value of 25 µg/$m^3$ set out in the Air Quality Directive, which will be reduced to 20 µg/$m^3$ in 2020.

The Pollution Regulations, Chapter 7

The Regulations relating to pollution control (Pollution Regulations), Chapter 7. Local air quality[11], laid down under the Act concerning protection against pollution and concerning waste (Pollution Control Act)[18], contains provisions on distribution of responsibility and execution of measuring programmes and the legally binding limit values for outdoor air. The purpose of the provisions in chapter 7 "is to promote the health and well-being of people and to protect vegetation and ecosystems by setting minimum requirements and target values for air quality and ensuring that they are complied with (...)".

The limit values are maximum concentrations in outdoor air for given averaging periods, in some cases with margin of tolerance. Section 7-6 of the Pollution Regulations lays down limit values for the components $SO_2$, $NO_2$ and $NO_x$, $PM_{10}$ and $PM_{2.5}$, lead, benzene and carbon monoxide (CO), see table 1.

**Table 1. Action limit values for outdoor air, pursuant to the Regulations relating to pollution control (Pollution Regulations) section 7-6.**[11]

| Component | Averaging period | Limit value | Margin of tolerance |
|---|---|---|---|
| ***Sulphur dioxide*** | | | |
| 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 and nitrogen oxides*** | | | |
| 1. Hourly limit value for the protection of human health | 1 hour | 200 µg/m³ $NO_2$ | 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 $NO_2$ | |
| 3. Limit value for the protection of vegetation | Calendar year | 30 µg/m³ $NO_x$ | |
| ***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 | |
| ***Lead*** | | | |
| Annual limit value for the protection of human health | Calendar year | 0.5 µg/m³ | |
| ***Benzene*** | | | |
| Annual limit value for the protection of human health | Calendar year | 5 µg/m³ | |
| ***Carbon monoxide*** | | | |
| Limit value for the protection of human health | Maximum daily 8-hour mean | 10 mg/m³ | |

Section 7-7 of the Pollution Regulations also indicate target values for arsenic, cadmium, nickel and benzo(a)pyrene (Table 2), which should be complied with "provided that this does not involve disproportionally great additional costs".

**Table 2. Target values for outdoor air, pursuant to the Regulations relating to pollution control (Pollution Regulations) section 7-7.**[11]

| Component | Averaging period | Target values |
|---|---|---|
| Arsenic | Calendar year | 6 ng/m³ |
| Cadmium | Calendar year | 5 ng/m³ |
| Nickel | Calendar year | 20 ng/m³ |
| Benzo(a)pyrene | Calendar year | 1 ng/m³ |

## Guidelines T-1520

The Guidelines for management of air quality in area planning (T-1520) are used as a guide to consider local air quality in the processing of building applications and area planning.[13] The guidelines specify limits for yellow and red zone for air quality based on levels of $PM_{10}$ and $NO_2$ (Table 3). The lower limit for the red zone corresponds to the limit value for $NO_2$ pursuant to section 7-6 of the Pollution Regulations, while the limit for red zone for $PM_{10}$ set out in T-1520 has a stricter margin of tolerance than the legal limit value. In the yellow zone, people with severe respiratory and cardiovascular disease have increased risk of aggravation of the disease, whereas healthy persons will probably not experience any adverse health effects. In the red zone, people with respiratory and cardiovascular disease have increased risk of adverse health effects, mostly children with respiratory disorders and elderly with respiratory and cardiovascular disease.

**Table 3. Lower limits for yellow and red zone for assessment of local air quality, pursuant to the Guidelines for management of air quality in area planning (T-1520).**[13]

| Component | Air pollution zone | |
|---|---|---|
| | **Yellow zone** | **Red zone** |
| $PM_{10}$ | 35 µg/m³ 7 days per year | 50 µg/m³ 7 days per year |
| $NO_2$ | 40 µg/m³ winter mean value[1] | 40 µg/m³ annual mean value |
| Health risk | Persons with severe respiratory and cardiovascular disease have increased risk of aggravation of the disease. Healthy persons will most likely not have any adverse health effects. | Persons with respiratory and cardiovascular disease have increased risk of adverse health effects. Among these, children with respiratory disorders and elderly with respiratory and cardiovascular disease are the most vulnerable. |

[1] The winter mean value excludes values from 1 May to and including 31 October.

## Air quality criteria

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"[14] (Table 4). 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.

**Table 4. The air quality criteria, drawn up by the Norwegian Institute of Health and the Norwegian Environment Agency (2013).**[14]

| Component | Averaging period | Air quality criteria |
|---|---|---|
| $PM_{10}$ | Day | 30 µg/m³ |
| $PM_{10}$ | Year | 20 µg/m³ |
| $PM_{2.5}$ | Day | 15 µg/m³ |
| $PM_{2.5}$ | Year | 8 µg/m³ |
| CO | 15 min | 80 mg/m³ |
| CO | Hour | 25 mg/m³ |
| CO | 8 hours | 10 mg/m³ |
| $NO_2$ | 15 min | 300 µg/m³ |
| $NO_2$ | Hour | 100 µg/m³ |
| $NO_2$ | Year | 40 µg/m³ |

| | | |
|---|---|---|
| Ozone | Hour | 100 µg/m$^3$ |
| Ozone | 8 hours | 80 µg/m$^3$ |
| $SO_2$ | 15 min | 300 µg/m$^3$ |
| $SO_2$ | Day | 20 µg/m$^3$ |
| B[a]P | Year | 0.1 ng/m$^3$ |
| Arsenic | Year | 2 ng/m$^3$ |
| Lead | Year | 0.1 µg/m$^3$ |
| Cadmium | Year | 2.5 ng/m$^3$ |
| Chromium (Cr(VI)) | Year | 0.1 ng/m$^3$ |
| Mercury | Year | 0.2 µg/m$^3$ |
| Manganese | Year | 0.15 µg/m$^3$ |
| Nickel | Year | 10 ng/m$^3$ |
| Vanadium | Day | 0.2 µg/m$^3$ |

Alert classes for air quality

The website luftkvalitet.info is developed and operated by the Norwegian Institute for Air Research (NILU), on behalf of the Norwegian Environment Agency and in cooperation with the Norwegian Public Roads Administration, the municipalities and the industry.[19] The website luftkvalitet.info presents the results of the measurements being made of the air quality in Norway along with other important information about local air quality.

To be able to provide good and clear information about local air quality and notify the public about episodes where the level of air pollution could pose a health risk, the Norwegian Institute of Health, the Norwegian Public Roads Administration and the Norwegian Environment Agency have drawn up national alert classes, last amended in 2015.[15] The alert classes reflect the newest knowledge on lower limits for health effects. The classes are set up as concentration intervals for daily or hourly mean values for the components $PM_{10}$, $PM_{2.5}$, $NO_2$, $SO_2$ and $O_3$, and are given for four different colour-coded levels: small, moderate, high, very high, with corresponding categories for health risk: small, moderate, significant and serious, respectively, see Table 5.

**Table 5. Alert classes for air quality, drawn up the Norwegian Institute of Health, the Norwegian Public Roads Administration and the Norwegian Environment Agency (2015).**[15]

| Alert classes | Level of pollution | Health risk | $PM_{10}$ Day (µg/m$^3$) | $PM_{2.5}$ Day (µg/m$^3$) | $PM_{10}$ Hour* (µg/m$^3$) | $PM_{2.5}$ Hour* (µg/m$^3$) | $NO_2$ Hour (µg/m$^3$) | $SO_2$ Hour (µg/m$^3$) | $O_3$ Hour (µg/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|
| | **Small** | Small | < 30 | < 15 | < 50 | < 25 | < 100 | < 100 | < 100 |
| | **Moderate** | Moderate | 30-50 | 15-25 | 50-80 | 25-40 | 100-200 | 100-350 | 100-180 |
| | **High** | Significant | 50-150 | 25-75 | 80-400 | 40-150 | 200-400 | 350-500 | 180-240 |
| | **Very high** | Serious | > 150 | > 75 | > 400 | > 150 | > 400 | > 500 | > 240 |

* The hourly levels for $PM_{10}$ and $PM_{2.5}$ are calculated on the basis of the daily levels, so that these conform for Norwegian conditions.

## 2.2.2 Discharges to sea

The regulations related to various types of discharge to sea from shipping are set out in MARPOL Annex I to V[9], which, like Annex VI on control of air pollution, apply as regulation in Norway. Like for the legislation for emissions to air, there are separate and more stringent provisions for discharges to sea from vessels in the defined emission control areas.

MARPOL Annex I relates to discharge and pollution by oil and oily mixtures from vessels. The requirements for discharge of oily bilge water are also included here, where an upper limit of 15 ppm has been set for oil in the water.

Annex II contains provisions for the handling and discharge of noxious substances in bulk.

Annex III contains regulations for the prevention of pollution by harmful substances carried by sea in packaged form. The Annex regulates the management of harmful substances that are carried in packaged form on board ships, including packing, marking and labelling, documentation, stowage and quantity limitations.

Annex IV contains provisions on management and treatment of sewage, sewage systems, and the discharge of wastewater from ships.

Annex V covers the regulations related to disposal of various types of garbage into the sea and procedures for disposal. The disposal into the sea of all plastics is prohibited. Only the disposal of food wastes is permitted under certain conditions, as well as wash water and cargo residues that are not harmful to the environment.

The Regulations on the prevention of transfer of alien organisms via ballast water and sediments from ships (Ballast Water Regulations) contain provisions for the handling of ballast water in Norwegian territorial waters.[20] Ballast water exchange shall on the whole only be conducted at least 200 nautical miles from the nearest land and in water at least 200 metres in depth. If treatment of ballast water is used, detailed provisions on technology and discharge apply. Ballast water may be delivered to approved reception facilities.

# 3. SELECTED FJORD AREAS AND CURRENT SITUATION

Norway's coast has a large number of fjords, and many of the fjord areas are popular tourist destinations. Several fjords have relatively heavy ship traffic, both small craft, high-speed craft, ferries, Hurtigruten's ships and large cruise ships.

In some fjord areas, the inhabitants and tourists have experienced periods with significant amounts of visible emissions, particularly from cruise ships, with smoke clouds that have covered large parts of the areas. This is perceived as visually disfiguring, and causes worry of possible harm to human health and harmful effects on nature in the fjords and mountains.

The fjords that were examined in this study; the Geirangerfjord, the Aurlandsfjord in to Flåm and the Nærøyfjord, were selected based on the number of cruise calls during the summer season and their status as world heritage sites.

The Geirangerfjord is a fjord in the municipality of Stranda in the county of Møre og Romsdal. It constitutes one of the two innermost, narrow arms of the Synnulvsfjord, which in turn is one of the arms of the Storfjord. The actual Geirangerfjord is 15 kilometres long. The fjord is surrounded by steep mountainsides, with heights of up to 1700 metres above sea level. At the end of the fjord, to the southeast, is the village of Geiranger, with a population of just over 200. There are also some houses at Møllsæter along the road of Ørnevegen on the north side of the fjord. A large number of tourists visits the Geirangerfjord and Geiranger every year. Many arrive by boat, including car ferries, and in the summer season by cruise ships and Hurtigruten's ships.

Further south is the Aurlandsfjord, an arm southeast in the Sognefjord in the county of Sogn og Fjordane. The Nærøyfjord is a sidearm of the Aurlandsfjord southwest in the municipality of Aurland. At the end of the Nærøyfjord, to the south, is the small village of Gudvangen, while Nærøy is situated further north in the fjord. In the east, the Aurlandsfjord continues to the villages of Aurlandsvangen to the east and Flåm at the end of the fjord to the south. The fjords are deep and narrow, with steep mountainsides on all sides. The locations are popular tourist destinations, with a significant degree of cruise ship traffic.

Both the Geirangerfjord, the Aurlandsfjord and the Nærøyfjord are on UNESCO's World Heritage List. The decision was made in 2005, with the beautiful and unique fjord landscapes and special geology as reasons.

# 4. METHOD

Emissions to air and discharges to sea and the dispersion of air pollution in the selected fjord areas were studied by carrying out various activities: a survey directed at ship traffic in the three fjords in question, video monitoring of the Geirangerfjord area, estimation of emissions from all shipping, and modelling of the dispersion of air pollution emitted from cruise ships in all the three fjords. The dispersion modelling included meteorological WRF modelling, estimation of emissions from cruise ships by using AIS data and the IHS Fairplay database, and dispersion calculations with the CALPUFF model.

Information from the questionnaire was also used to complete and correct the estimated emissions from cruise ships. The emission calculations were also checked by comparing them to the pictures from the video monitoring. The results from the meteorological modelling and dispersion modelling were validated and assessed against measurements of meteorological parameters and air pollution made in the same period in the Geirangerfjord.

## 4.1 Survey: Emissions to air and discharges to sea from ships

A survey was conducted directed at passenger ships operating in Norwegian fjords in order to map operational data and procedures significant for emissions to air and discharges to sea. The survey was conducted by SINTEF MARINTEK as subcontractor to Rambøll, as part of the project for mapping pollution from cruise traffic in Norwegian fjord areas. The assignment, purpose, methodology and results related to the survey are described in detail in a separate report.[21] A summary of the underlying methodology, the distribution and the analysis of the questionnaires is given below.

A questionnaire was drawn up with the purpose of mapping technical information about the ships and their operational profile. The first part of the questionnaire contained general questions regarding the vessel's name, IMO number and year of construction. The main part consisted of questions related to specifications of ship machinery (the number of main and auxiliary engines, power, type), fuel (type, sulphur content), emission-reducing technology ($NO_x$, $SO_x$ and PM reduction systems) and discharges to sea (discharge of sewage and grey water, treatment systems). There were also questions regarding operational data specifically when underway and time in port in the Geirangerfjord.

The questionnaire was distributed to all passenger ships that visited the fjords in question during the period from May to September 2016. Cruise ships were sent web-based forms via their Norwegian agents, whereas Hurtigruten and local ferries and passenger boats were contacted directly. All of Hurtigruten's vessels responded to the survey, whereas the response rate for the cruise ships and local ferries was around 50%. Even though the response rate for the cruise ships was relatively low, the age of the ships that responded was comparable to the age of the global cruise ship fleet. The results from the survey are therefore considered representative for the cruise ships, but somewhat more uncertain for the local ferries, since there is no information about the vessels that did not respond.

Data for technical factors and operational profiles were reviewed and used for adjustment of the input data used to estimate emissions from cruise ships, see section 4-4.

## 4.2 Video monitoring of the Geirangerfjord

The ship traffic in the Geirangerfjord was monitored by way of video during parts of the cruise season 2016. A GoPro Hero5 Black camera was mounted and installed at a private property south in Geiranger, with a view of the Geirangerfjord. The camera was pre-programmed to take pictures of the area every 30 minutes. It was installed on 4 August 2016, and took pictures every 30 minutes until the end of September. Professor Jörg Löffler from the University of Bonn, Germany, and Katrin Blomvik, general manager of the foundation Stifitinga Geirangerfjorden Verdsarv, carried out the installation of the camera and operated the video monitoring. Following the picture-taking, the pictures were analysed visually to make sure that they did not contain any identifiable information, and then a time-lapse was created that shows ship movements and visible emissions from the funnels in the time period. Pictures showing formation of significant smoke clouds from vessels were sorted out, and the time and the vessel's identity was noted down.

The purpose of the video monitoring was to be able to follow the ships' movements over time, and to visually observe smoke clouds emitted from the vessels operating in the Geirangerfjord. This way, documentation in the form of pictures was collected over a longer continuous time period in the cruise ship season that gave an indication of the size of the emissions and the dispersion, and whether the problem with large, visible smoke clouds was caused by individual vessels, weather conditions and/or coincidences. The video images were also used to verify the AIS data, and to assess the emission estimates and the dispersion calculations. The GoPro pictures were supplied with pictures focusing more on the fjord area sent in by the Norwegian Maritime Authority and Stiftinga Geirangerfjroden Verdsarv.

## 4.3 Meteorological modelling

### 4.3.1 Model configuration

The meteorological modelling was carried out by the Weather Research and Forecasting (WRF) Model with Advanced Research dynamic solver.[22] WRF is a next-generation mesoscale numerical weather prediction system designed for both operational weather forecasting and research on atmospheric conditions. The system features two separate modules that calculate various types of physical processes such as surface energy and soil interactions, turbulence, cloud microphysics and atmospheric radiation. The user can choose between many different systems depending on type of physical process. The WRF Preprocessing System (WPS) generates initial and lateral boundary conditions for use in WRF, based on topographic data sets, information on area use, and larger-scale atmospheric and oceanic models. In the following paragraph, we will present the model set-up, input data and parameters used for the WRF simulations for the selected Norwegian fjord areas for the summer season of 2016.

### 4.3.2 Selection of model

The publicly available version of WRF, version 3.8.1, was used for the meteorological simulation. This was the newest version of WRF that was available at the time of the simulation. WPS version 3.8.1 was also used for processing the input data for the model.

### 4.3.3 Configuration of horizontal domain

The WRF simulation in the selected Norwegian fjords consists of two sets of nested grids that are simulated simultaneously, with an inner horizontal resolution of 300 metres. The expansion of the WRF grids is scaled based on the main grids with a factor of three. In addition, both grids consist of five nested domains with a resolution of 24.3 km (d01), 8.1 km (d02), 2.7 km (d03), 900 m (d04) and 300 m (d05). The outermost domains, d01 and d02, are shared by both grids. The three innermost domains are specific for the Geirangerfjord grid and the Aurlandsfjord/Nærøyfjord grid with the 300 m grid centred over the approximate cruise ship destinations in the fjords. Figure 2 and Figure 4 show the three outer domains, d01, d02 and d03, for the Geirangerfjord and the Aurlandsfjord/Nærøyfjord, respectively. The 900-metre and 300-metre domains, d04 and d05, have been placed on top of a terrain map for each location in Figure 3 and Figure 5, respectively. The configuration for each nested domain includes a buffer of five grid cells in all directions to avoid numerical noise along the WRF domain boundaries that could affect the meteorological input data to the air quality model. Such numerical noise could occur near the boundaries of the WRF domain solution when the boundary conditions come into balance with the numerical algorithms in WRF. The grids were defined on a Lambert Conformal Conic (LCC) projection centred at 61°N, 8°E, with actual latitudes of 50°N and 70°N.

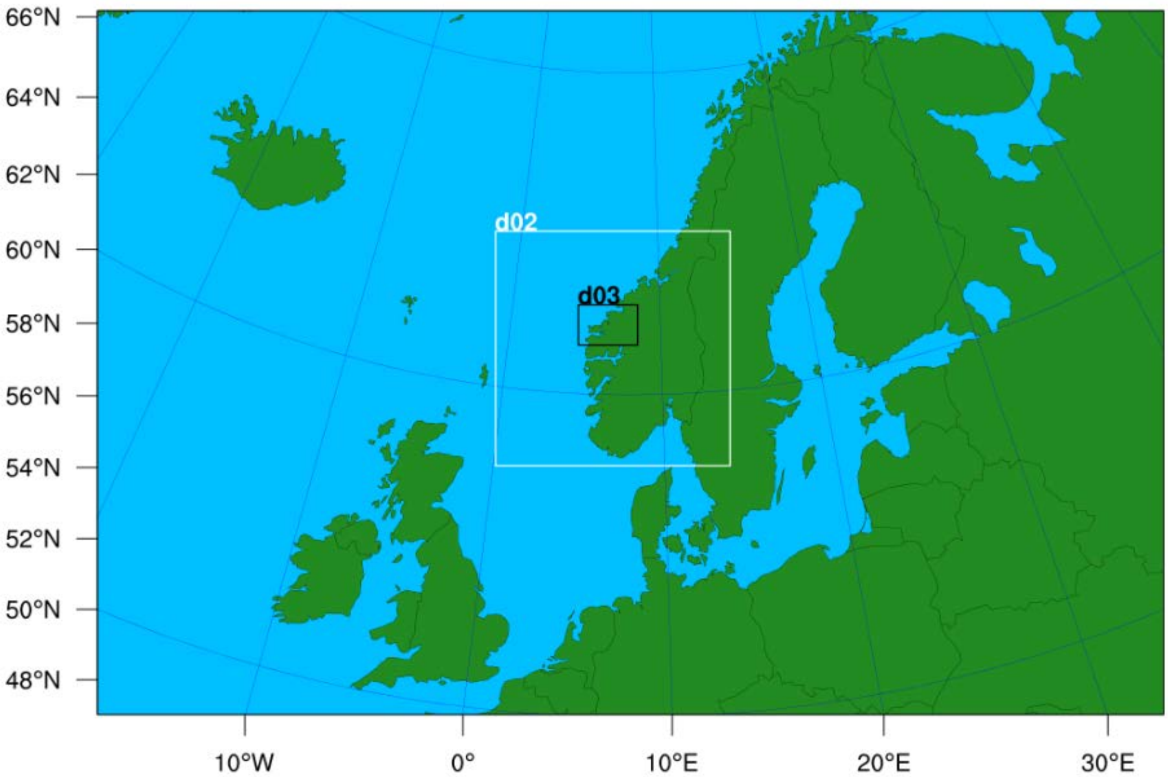


**Figure 2. The WRF modelling domains with 24.3 km (d01, outer edge of the picture), 8.1 km (d02) and 2.7 km (d03) resolution, for the Geirangerfjord grid.**

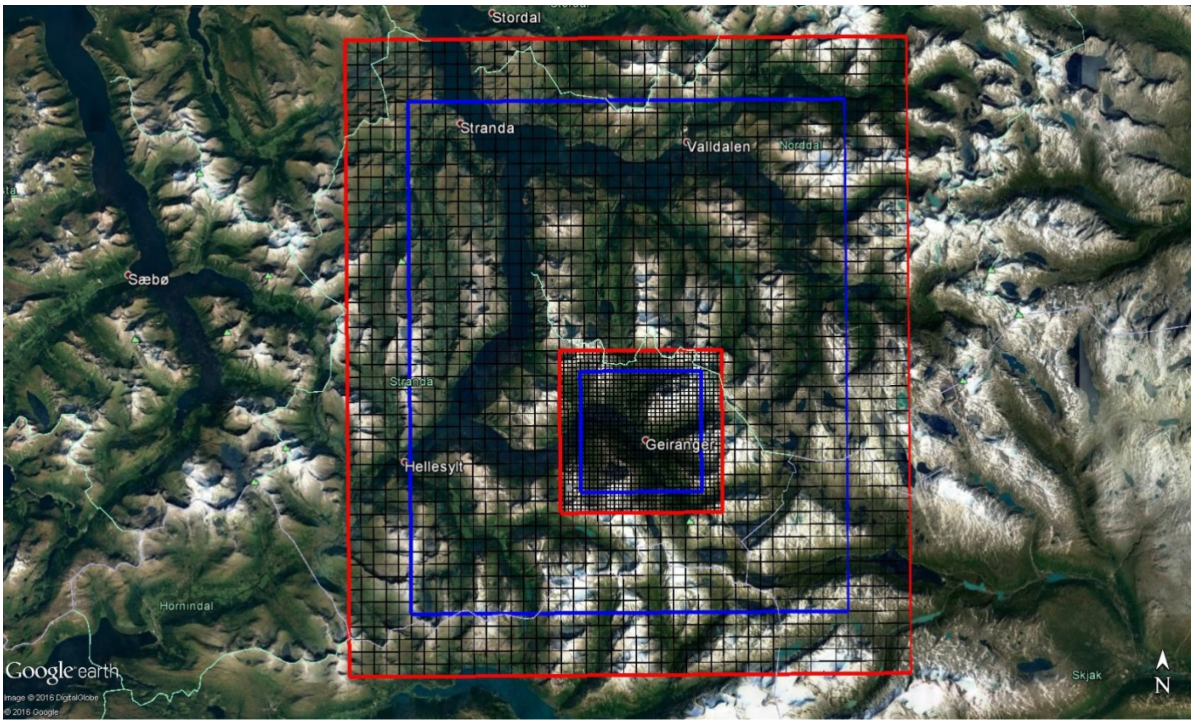

**Figure 3. The WRF modelling domains with 900 m and 300 m resolution (outermost and innermost square, respectively), for the Geirangerfjord grid. The red square marks the full WRF domain, while the blue square marks the calculation area actually used.**

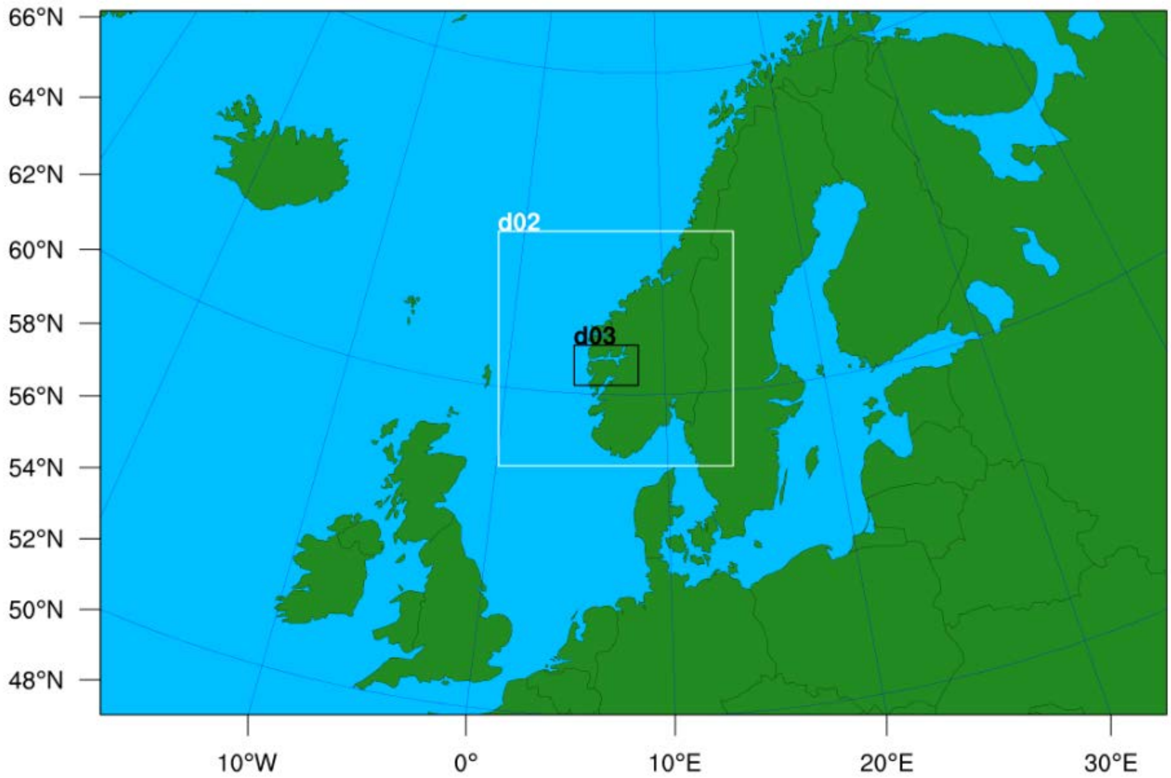


**Figure 4. The WRF modelling domains with 24.3 km (d01, outer edge of the picture), 8.1 km (d02) and 2.7 km (d03) resolution, for the Aurlandsfjord / Nærøyfjord grid.**

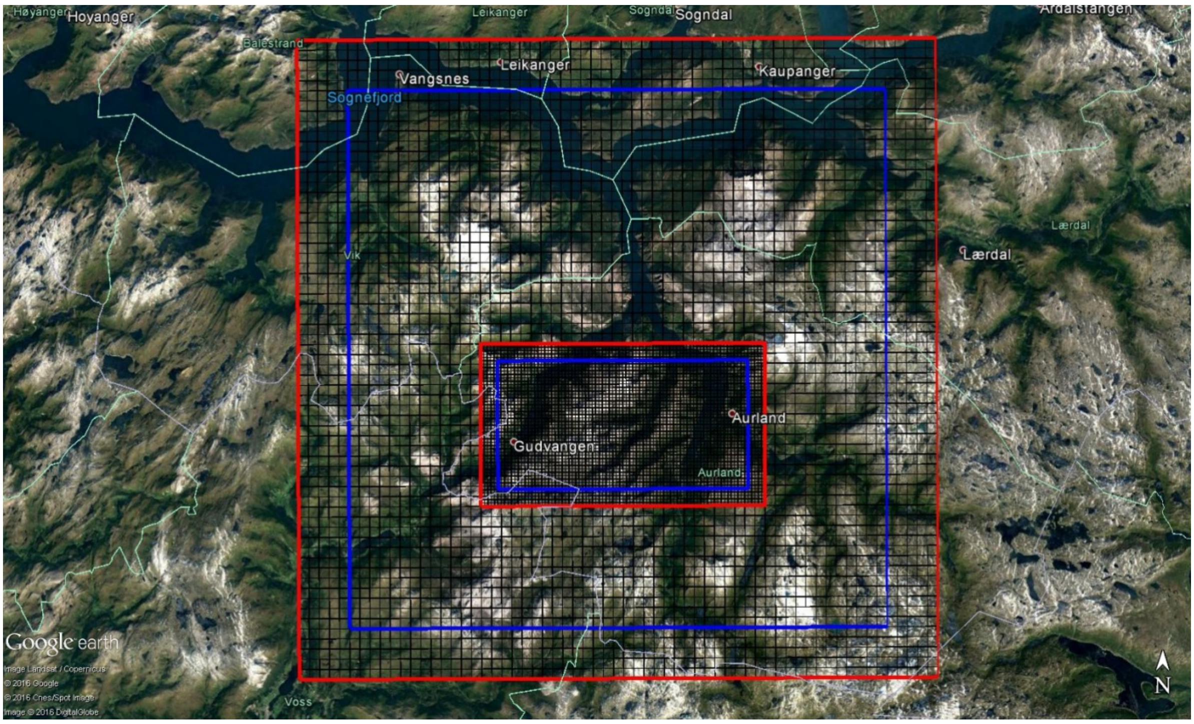


**Figure 5. The WRF modelling domains with 900 m and 300 m resolution (outermost and innermost square, respectively), for the Aurlandsfjord / Nærøyfjord grid. The red square marks the full WRF domain, while the blue square marks the calculation area actually used.**

### 4.3.4 Defining vertical domain

The WRF modelling was based on 33 vertical layers with a surface layer of around 40 metres in depth. The vertical domain, presented both as sigma (vertical coordinates in WRF; indicates a percentage of the difference in pressure between the planet's surface and the top of the model) and as approximate height coordinates, is shown in Table V2-1 in Appendix 2.

### 4.3.5 Topographic background material

The information on the topography for the WRF model was retrieved using standard WRF terrain databases. The three innermost domains were based on the newest Global 30 Arc-Second Elevation (GTOPO30) data[23], which are 30-second (approximate 900-metre) data. WPS carries out a numerical equalisation of the topographic input data in order to achieve numerical stability. It was attempted to use high-resolution (approx. 30-metre) elevation data from the ASTER satellite, but this caused too much numerical instability in the WRF simulations due to the extreme terrain in the fjord areas. Even if the resolution of the terrain input data is courser than the 300 m resolution of the grid, the fjord areas are nevertheless sufficiently represented in the model, as shown in Figure V5-1 and V5-2 in Appendix 5.

### 4.3.6 Vegetation type and land cover map

The map data for vegetation types and land cover were extracted from the United States Geological Survey (USGS) databases for land cover from the newest WRF databases that come with WRF classification. The 24.3 km and 8.1 km domains were based on 2-minute global data, while the more high-resolution domains were based on 30-second data.

### 4.3.7 Atmospheric conditions

WRF is dependent on results from other models or re-analyses for information about initial and boundary conditions. The first guess is taken from the European Centre for Medium Range Weather Forecasts' (ECMWF) archives for Interim re-analysis (ERA-Interim).[24]

### 4.3.8 Time integration

A 3rd order Runge-Kutta integration was used.

### 4.3.9 Selected diffusion

A horizontal Smagorinsky first order closure with 6th order numerical diffusion and prohibited up-gradient diffusion was used.

### 4.3.10 Water temperature

Water temperature data were retrieved from the Group for High Resolution Sea Surface Temperature (GHRSST)[25], which have a horizontal resolution of 1 km.

### 4.3.11 Data assimilation

The objective analysis program OBSGRID was run to enable incorporation of data from the observational archive Meteorological Assimilation Data Ingest System (MADIS)[26], including METAR, SAO and maritime observations. These data were thereafter incorporated into the ERA boundary conditions and used in the WRF data assimilation. Specifically, the WRF model was run with analysis nudging, i.e. Four Dimensional Data Assimilation (FDDA), for the 24.3 km and 8.1 km domains. On both domains, analysis nudging coefficients of $3x10^{-4}$ were used for wind and temperature, and similar for mixing ratio coefficients of $1.0x10^{-4}$. Analysis nudging was applied to wind, temperature and mixing ratio above the planetary boundary layer. There are not enough observations within each domain to use analysis nudging on the domains with resolution of 2.7 km and higher.

#### 4.3.12 Physics

The choices related to physics that were used in this application are presented in Table V2-2 in Appendix 2. Different cumulus parameterizations were used for the two fjord domains to avoid WRF model errors caused by vertical instability in the Nærøyfjord domain.

#### 4.3.13 Application

The WRF modelling was conducted in 5.5-day long periods that were started at 12.00 UTC (universal time) every five days. The model results were output data every 60 minutes, and the output files were divided into 12-hour intervals. A 12-hour spin-up was included in every 5-day period before the data were used in the subsequent evaluation.

#### 4.3.14 Validation of the WRF model

The WRF simulations for the selected fjord areas for the summer season of 2016 were validated using quantitative and qualitative methods. To sum up, the quantitative evaluation was carried out by comparing the predictions from the WRF simulations with observed meteorological data from relevant weather stations. Due to lack of meteorological stations measuring wind speed in the fjords in question, a qualitative analysis of the modelled wind was carried out by interpreting the results in relation to the terrain in the area.

The methodology and the results from the evaluation of the WRF model performance are described in detail in Appendix 3.

### 4.4 Estimation of emissions to air

Total emissions to air were estimated for all vessels that visited the world heritage fjords during the summer months June to August 2016. In this study, cruise ships and passenger ships included vessels registered exclusively as cruise or passenger ships in international ship databases, whereas remaining vessels, including ships registered as a combination type such as passenger/ro-ro ships, are referred to as ‘other vessels’. Local ferries and Hurtiguten's ships are registered as combination types, and are therefore included in the category other vessels.

For cruise ships and passenger ships, the emissions of the components $NO_x$, $SO_2$, $PM_{10}$ and $PM_{2.5}$ were estimated using ship identification data and information on each ship available in ship databases. $NO_x$ emissions from other vessels were estimated using available emission factors for $NO_x$ and ship data from the survey directed at the ships in the areas in question. Emissions of $NO_x$, $PM_{10}$ and $PM_{2.5}$ from traffic on land in the world heritage sites were estimated based on traffic data and emission factors for road traffic.

#### 4.4.1 $NO_x$ emissions from other vessels

$NO_x$ constitutes the most predominant emissions to air from shipping. The emissions to air of $NO_x$ from other vessels such as local ferries and Hurtigruten's ships that visited the world heritage sites the Geirangerfjord, Aurlandsfjord and Nærøyfjord from 1 June to and including 31 August 2016 were estimated based on data from the survey referred to in section 4.1 and established emission factors.

Ships visiting the Geirangerfjord, Aurlandsfjord and Nærøyfjord in the summer season include local ferries and fjord cruises, as well as Hurtigruten's ships in the Geirangerfjord. In the questionnaire, these vessels were asked to estimate fuel consumption for each round trip. For Hurtigruten, fuel consumption within the zone in the innermost part of the Geirangerfjord was estimated. The number of trips in the areas was read from timetables. The total emissions of $NO_x$ from traffic in the world heritage fjords during the period from June to August 2016 were estimated based on these data and $NO_x$ emission factors taken from the EMEP/EEA air pollutant emission inventory guidebook[27]. For Hurtigruten, the average $NO_x$ emission factor was calculated based on collected data from the questionnaire on the number of engines, model year, rated power and rated speed, see background data and calculation in Table V4-1.

### 4.4.2 Emissions to air from cruise and passenger ships

AIS data were ordered and sent from the Norwegian Coastal Administration's network AIS Norge[28]. The data set contained vessel identification in the form of IMO and MMSI number, position, course and speed with high resolution. The program language Python was used to process the large dataset. The dataset was reduced to containing only movements within the defined calculation areas. The calculation areas for estimation of emissions from cruise ships using AIS data are the same as described in the section on meteorological modelling.

In order to calculate emissions, vessel characteristics such as vessel type, year of construction, gross tonnage, propulsion engine power, engine type, engine speed and speed were also needed. This information was obtained by grouping the MMSI and IMO numbers from the AIS data with the IHS Fairplay register data[29]. These data, together with data from the survey conducted by SINTEF, could be used as basis for estimating the emissions from the cruise ship traffic within the calculation areas for the months of June to August 2016.

The analysis of the data included pre-processing, determination of voyages, determination of arrivals and departures, activity calculation and estimation of emissions.

<u>Pre-processing of data</u>

The AIS data received from the Norwegian Coastal Administration contained 402.7 million registrations of ship movements for the period from 1 June to 31 August 2016 that covered the calculation areas for the two fjord areas. The data were first combined with Fairplay register data in order to include the necessary vessel characteristics. Vessels identified as "cruise ship" or "passenger ship" in the Fairplay database were kept in the dataset.

<u>Determination of voyages</u>

Individual vessel voyages that included the calculation areas were determined in order to estimate speed profiles based on the data for location and time. In this connection, a "voyage" is defined as an individual vessel's set of connected points travelled within the calculation areas. Data registrations outside the calculation areas were removed from the dataset. Voyages that consisted or 10 or less registrations (normally less than one hour in the calculation area) were left out and considered incomplete.

<u>Activity analyses</u>

The activity, in kWh, was determined between each data registration for a voyage for use together with emission factors. The average duration from point to point was estimated using the difference in the indication of time between each registration for a voyage. Engine power was estimated for propulsion engines, auxiliary engines and steam boilers by multiplying the load (in kW) with time for each sequence. The details of these calculations are described in the next section.

*Propulsion engines*

The activity of the propulsion engines was calculated on the basis of total main engine power and load factor. The main engine power was reported for nearly all the vessels in the Fairplay database. For vessels that lacked information on main engine power (in 0.3% of the cases), estimates based on type of vessel from the United stated Environmental Protection Agency (US EPA)s Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories (EPA CMEI)[30] were used, see Table V4-2 in Appendix 4.

The load factor associated with the engines was estimated using the propeller law.

$$Load\ factor = \left(\frac{Actual\ speed}{Maximum\ speed}\right)^3$$

The actual speed is retrieved from the AIS data. The service speed, i.e. the speed a ship maintains over long distances, is reported in the Fairplay database, and is considered to be 94% of the maximum speed.[30] Calculation back to maximum speed gives the load factor for each registration, and by multiplying the propulsion power with the load factor, we get a rough estimate of the activity. Additional adjustments due to lower engine efficiency at low loads are carried out based on polluting components, as explained in more detail in the section on emissions.

*Auxiliary engines and steam boilers*
Auxiliary engine and steam boiler power reported in the Fairplay database is often incomplete and, in some cases, erroneous. The survey conducted by SINTEF gave some indications of auxiliary engine power, but these data varied from 450 kW to more than 75,000 kW. This is due to the fact that there are large differences in ship size and that certain ships with diesel-electric propulsion systems define all engines as auxiliary engines. In order to obtain more complete data for engine power for the AIS registrations, numbers for load factors for auxiliary engines and engine load for steam boilers were retrieved from EPA CMEI, see Table V4-3 and V-4-4, respectively, in Appendix 4. Standard load factors for auxiliary engines are classified by speed: service speed (>12 knots), zone for reduced speed (>9 knots and < 12 knots) or manoeuvring (>1 knots and < 9 knots). Standard energy consumption rates for steam boilers reported in EPA CMEI were derived from energy consumption data, and the engine load was thus determined without use of load factors. The activity from steam boilers was only calculated for vessels during manoeuvring and in hotel mode since it is assumed that steam boilers are not in use when the propulsion engines generate enough heat (e.g. during service speed and zones for reduced speed). The steam boiler load is the same for stays in port and in manoeuvring mode.

Emissions
Emissions associated with the passage between subsequent registrations in a voyage were determined using the calculated activity as explained in the previous section, and emission factors in g/kWh. Emission factors were selected based on engine speed, fuel, sulphur content of fuel (0.25% sulphur based on average voyage weighted fuel consumption from the survey data), and propulsion engine load. Pre-controlled emissions factors for the various engine types are shown in table V4-5 in Appendix 4.

Engine speed, in rounds per minute (rpm), were mainly retrieved from the Fairplay database. The registrations were defined as slow (<130 rpm), medium (130-1400 rpm) or high (> 1400 rpm) based on reported engine speed. Data not found in the Fairplay register were covered based on type of engine: For two-stroke engines, a low speed was assumed, and for four-stroke engines, medium speed was selected, since this is the most common for the main engines of most ships. For the remaining registrations that were missing either engine speed or stroke cycles in the Fairplay database, the most often registered speed was entered (counted as engine speed in relation to number of voyages, not number of registrations), i.e. medium speed.

When a calculated load factor is less than 20%, the ship's engine effect is reduced and the emission rate is adjusted upwards. In order to compensate for this reduced effect, registrations with such low loads were multiplied by adjustment factors, see Table V4-6 in Appendix 4.

The emissions from travelling from one point to the next within a voyage were estimated by multiplying activity data derived from the registrations in the Fairplay database with the emission factors. The resulting emission segments for each voyage, for each type of vessel, were aggregated into a 100-metre grid laid over the calculation area to get the total emissions for each grid cell.

### 4.4.3 Emissions to air from road traffic

Emissions to air from vehicle traffic on the roads in the fjord areas in question were estimated in order to examine the relative contribution from road traffic compared to the emissions from shipping. Calculations of emissions of $PM_{10}$, $PM_{2.5}$ and $NO_x$ to air from exhaust and emissions of $PM_{10}$ from wear of tyres, brake pads and asphalt from the roads in the areas were carried out. Emissions of $SO_2$ from road traffic are more or less zero.

Traffic numbers from the main roads in the area, for which numbers are available, were retrieved from the Norwegian Public Roads Administration's National road data bank (NVDB)[31]. Available traffic numbers adjusted by season were submitted by the Norwegian Public Roads Administration. Emissions of $PM_{10}$, $PM_{2.5}$ and $NO_x$ in exhaust from vehicles from burning of fossil fuel are calculated based on emission factors from the Handbook Emissions Factors for Road Transport[32]. Emission factors for 2015 were used. For the emission of particulate matter from wear of tyres, brake pads and asphalt, emission factors were retrieved from the Norwegian Emission Inventory 2016[33] and the EMEP/EEA air pollutant emission inventory guidebook 2016[34], see Table V4-7 in Appendix 4. The stretches of road that were included in the calculations are listed in Table V4-8 in Appendix 4.

## 4.5 Dispersion modelling

In order to assess the local air quality in the world heritage sites the Geirangerfjord, the Aurlandsfjord and the Nærøyfjord, the dispersion of $NO_2$, $SO_2$, $PM_{10}$ and $PM_{2.5}$ emitted from cruise and passenger ship traffic in the period from June to August 2016 was calculated in accordance with the applicable legislation.

### 4.5.1 The CALPUFF system

The dispersion calculations were carried out with the dispersion model CALPUFF, a non-steady-state Lagrangian puff model[35]. The CALPUFF modelling system can take into account secondary aerosol formation, gaseous and particle deposition, wet and dry deposition processes, complex three-dimensional wind regimes and air humidity. The calculations were carried out for gridded receptor points in the three fjord areas. The terrain maps used in CALPUFF for the two calculation areas (the Geirangerfjord and the Aurlandsfjord/Nærøyfjord) are shown in Figure V5-1 and V5-2, respectively, in Appendix 5. Since the distance between the receptor points was relatively short, the effects of secondary aerosol formation were not included. For the modelling, USEPA's newest standard version of CALPUFF, version 5.8.4 (released on 14 December 2015), was used, in combination with CALPOST version 6.221, level 080724 for post-processing, and USEPA's Mesoscale Model Interface Program (MMIF) version 3.3[36] for converting the WRF modelling results to a format that could be imported into CALPUFF.

The calculated emissions based on AIS data were summed up on an hourly basis within each grid cell with 100-metre resolution that covered the actual fjords. The emissions were modelled as time-varying point sources. The processing of the AIS data resulted in a cell-by-cell and hour-by-hour emission file (PTEMARB.DAT) that was prepared in accordance with the format required for use in CALPUFF. Each cell worked as an individual source and was modelled from the centre. On an hourly basis, grid cells that did not have any AIS reported vessels were given an emission ratio of zero. Parameters for the ships' funnels (height, diameter and emission temperature and speed) were determined by relating the vessels' identification number in AIS to the vessel parameters in the Fairplay database. Vessels not found in the database were cross-referenced with data from SINTEF's survey. When the height of the funnels had been determined, the average height for the fjords was estimated and used. It was necessary to use the average since the emissions were summed up for each grid cell, and each cell could contain more than one vessel. The funnel parameters used in the analysis are listed in Table V5-1 in Appendix 5.

### 4.5.2 Post-processing

The modelling results were processed using CALUTIL and CALPOST. These tools enabled calculation and extraction of concentration measurements that were comparable to applicable limit values. Gridded and discrete receptors were used in CALPUFF's calculation area. The gridded receptors were assessed at 100-metre intervals, while the discrete receptors were used at selected locations either to compare with available measurement results or to assess impacts at specific sensitive places (inhabited areas). The pictures from the GoPro camera that was installed in the Geirangerfjord in parts of the cruise season were also used to verify the identity of the emissions from the cruise ships.

### 4.5.3 Converting calculated results for $NO_x$ to concentrations of $NO_2$

The emission factors apply to $NO_x$ as a whole, and concentrations calculated by CALPUFF are therefore for $NO_x$. However, the limit values apply to $NO_2$, and the calculated concentrations of $NO_x$ therefore have to be converted to $NO_2$ concentrations in order to relate the dispersion maps to limit values.

CALPUFF used the Ambient Ratio Method version 2 (ARM2)[37], which is the method recommended by USEPA for $NO_x$ to $NO_2$ conversion for hourly mean data. The method was developed based on an analysis of hourly ambient $NO_x$ and $NO_2$ monitoring data from 580 measurement stations over a period of ten years. A polynomial equation was fitted to the upper part of a curve of the relation between measured $NO_2/NO_x$ ratio and $NO_x$ concentrations in ppb:

$$NO^2 = -5.176 \times 10^{-16NO_x^6} + 1.005 \times 10^{-12NO_x^5} - 7.288 \times 10^{-10NO_x^4} + 2.296 \times 10^{-07NO_x^3} - 1.981 \times 10^{-05NO_x^2} - 5.148 \times 10^{-03NO_x} + 1.244 \times 10^{+00}$$

The percentage of $NO_2$ is thus reduced with an increased concentration of $NO_x$ in the air. USEPA recommends a maximum $NO_2/NO_x$ radio of 0.9 and a minimum ratio of 0.2.

# 5. RESULTS

In the following, the results from the various activities related to the mapping of emissions to air and discharges to sea from ships in the world heritage fjords the Geirangerfjord, the Aurlandsfjord and the Nærøyfjord for the summer of 2016 are presented. Calculations of emissions from all vessels and road traffic on land, modelling of dispersion of emissions from cruise and passenger ships in the world heritage sites (June-August), the survey directed at the shipping activities in the three fjords (May-September) and video monitoring in the Geirangerfjord (start of August to end of September) were carried out in connection with the assignment from the Norwegian Maritime Authority. Parts of the results from the mapping were validated and/or assessed against ongoing measurements of meteorology and air pollution in the Geirangerfjord.

## 5.1 Survey: Emissions to air and discharges to sea from ships

The following paragraph sums up the main findings from the questionnaire that was distributed to passenger ships that visited the three fjords in the summer season of 2016. A detailed presentation of results from the survey is presented in a separate report.[21]

A total of 72 unique cruise ships, 11 Hurtigruten ships and 13 local ships (ferries and similar) were registered in the Geirangerfjord, Aurlandsfjord and Nærøyfjord in the period from 1 May to 30 September 2016. We received responses from all the Hurtigruten ships, whereas the response rate was just over 50% for cruise ships and the local passenger ships. Even though the response rate for the cruise ships and local ships was relatively low, the submitted data for the cruise ships were considered to be sufficiently representative based on the age distribution of the ships. The percentage of emissions to air contributed by the local ferries could be estimated with a high degree of certainty for the vessels that responded to the survey, whereas the estimates for the ships that did not respond are associated with some uncertainty.

### 5.1.1 Cruise ships

The ships' age is very significant for the emission to air, since the requirements for ship machinery and pollution-reducing technology are dependent on year of construction. Approx. 60% of the ships that responded to the survey were constructed before the year of 2000, and are therefore not required to comply with the Tier I requirements. In comparison, approx. 50% of all the cruise ships that visited in 2016 were constructed before 2000. The ship machinery's power, both main and auxiliary engines, generally increased proportionally with the ships' tonnage and passenger capacity. Most ships have four or more main engines and auxiliary engines. Fuel used is mostly distillate (marine gas oil), whereas 12% use heavy fuel oil.

The survey made it clear that the vast majority of ships use bunker oil with less than 0.10% sulphur when the ship is at anchor or berth. When bunker oil with a higher sulphur content is used, scrubber systems are installed on board. $NO_x$ emission level (Tier I, II, III) is connected with the age of the ships (year of construction). 20-25% of the ships state that they have $NO_x$ reduction technology installed. This can be SCR systems, EGS systems or other $NO_x$ reducing measures.

SCR systems will reduce the $NO_x$ emission factor with around 85-90%, so that the engines satisfy the IMO Tier III requirements, and 9-12% of the ships had such systems installed for their main and auxiliary engines. EGS systems have less $NO_x$-reducing effect, but with such systems, the IMO Tier II requirements can be met, and 9% of the ships stated that they had such systems for both the main and auxiliary engines. In addition, 3-6% had implemented other $NO_x$ reducing measures for the main and auxiliary engines on board.

The final part of the questionnaire was related to operational profile for the visits to the fjords in question. When travelling in the innermost part of the Geirangerfjord (zone 4 of the questionnaire) the average speed was 10 knots. Most ships spent between four and ten hours in port. The average power of propulsion and auxiliary engines when travelling within zone 4 was 8,611 kW and 5,594 kW, respectively. Speed and engine power in the Aurlandsfjord/Nærøyfjord was approximately the same as for the Geirangerfjord. For the Nærøyfjord in particular, there were relatively few reported data, since there is considerably less ship traffic here compared to the other world heritage fjords.

Lower speeds resulted in lower power demand, which in turn contributes to lower fuel consumption. On the other hand, the specific fuel consumption for the engines will increase at low loads, the same also applies to the specific emissions of $NO_x$, PM and soot. The navigation time will also increase. For example, a reduction of the speed from 10 to 5 knots will most likely contribute to reduced overall emissions, but it is not possible to estimate the net profit without detailed data for ship and machinery on board. In order to get a correct picture, we recommend carrying out analyses based on data for off-design operation for ships and machinery.

Discharges to sea

Discharges to sea were also mapped in the survey. Relevant types of discharge are cleaned, treated and untreated sewage, grey water and discharge connected to scrubber systems on board. All the cruise ships that responded stated that they have sewage treatment systems specified in accordance with various applicable IMO requirements.

More than 90% stated that they discharge no treated or untreated sewage, and 94% stated that they do not discharge grey water when operating in the fjords in question.

The responses to 'Discharge to sea from scrubbers' show that a low percentage of the ships have such systems installed or use them in the fjords, as most ships use MGO with a low sulphur content in these areas. Comments describe possibilities for running "closed loop" in port and sheltered waters with accumulation, and "open loop" with discharge to sea in other areas. Discharges to sea are treated in accordance with applicable requirements.

### 5.1.2 Other vessels

Seven of the thirteen local ferries or other vessels in regular scheduled service that were registered, responded to the survey. All of these vessels use fuel with a sulphur content of less than 0.05%. None of them had any $NO_x$ reduction system installed, so that the standard emission factor for the ship types will provide a good estimate of emissions to air.

Information was also retrieved from local vessels in regular scheduled service and from Hurtigruten on operational data for speed, time in port and engine specifications, to enable calculation of approximate fuel consumption and emissions to air. These estimates can be used as input data in dispersion modelling.

Discharges to sea from the ferries were stated as treated sewage and grey water, approx. 0.5-2 $m^3$ per day in the Geirangerfjord and up to 6 $m^3$ per day in the outermost parts of the Aurlandsfjord. One of the ferries also stated that it discharges small amounts of bilge water (0.1 $m^3$). For ferries and local boats, the ferries that responded stated that they discharge small amounts of treated sewage, but they did not specify which systems they had on board.

Three of the Hurtigruten ships visiting Geiranger discharge treated sewage and grey water in all zones. None of the ships discharges bilge water. All the Hurtigruten ships have sewage systems in accordance with MARPOL (MEPC.159(55), MEPC.2(VI), MEPC.227(64)), except the two oldest ships that have holding tanks on board.

## 5.2 Video monitoring of the Geirangerfjord

The pictures from the GoPro camera that was installed south of the Geirangerfjord from the start of August to the end of September showed that some vessels periodically caused formation of visible smoke clouds. Both in clear weather and in overcast conditions, smoke clouds could be observed. Pictures taken during the summer of 2016 submitted by the Norwegian Maritime Authority and the foundation Stiftinga Geirangerfjorden Verdsarv clearly documented such


a)


b)

**Figure 6. Examples of pictures showing formation of visible smoke clouds by the emissions from vessels travelling in the Geirangerfjord. a) is submitted by the Norwegian Maritime Authority and Stiftinga Geirangerfjorden Verdsarv, whereas b) is taken by the GoPro camera installed south of the Geirangerfjord, that took a picture every 30 minutes in the period from 4 August to 30 September 2016. Date and time of picture b) is indicated on the picture.**

episodes in more detail. Examples of such episodes with observable smoke clouds forming above the fjord are shown in Figure 6 and in Appendix 1.

Of the cruise ships that visited the Geirangerfjord in the period, just over 20 unique vessels (of 181 vessels with AIS transponders) formed pronounced smoke clouds; some of these visited the area several times during the cruise season. There is often more than one cruise ship present at the same time in the Geirangerfjord that can emit visible smoke. Based on the pictures, it was evident that some of the local ferries as well, which are not registered in the ship database containing only cruise ships / passenger ships, generate clearly visible emissions.

Smoke indicates visible exhaust gases from combustion or industry processes.[38] The main components are gases, such as nitrogen, oxygen, carbon dioxide and water vapour. The particles in smoke are visible; these can consist of ash, unburned substances and soot.

The gases in smoke from combustion in engines have no colour when emitted to air in the present concentrations. However, particles and liquids in or from the exhaust gases can or will be visible. Soot forms black particles and smoke that becomes black or grey depending on the concentration. Unburned hydrocarbons form a bluish smoke. Water vapour will often condense to small droplets when cooled down some distance away from the funnel, and turns into liquid. The water vapour will then form a white cloud, or grey if the cloud becomes sufficiently concentrated or thick. NO is a colourless gas, whereas $NO_2$ is a reddish brown gas. Most of the $NO_x$ is in the form of NO coming out of the funnel, but is partially converted to $NO_2$ in the atmosphere little by little.

In all pictures with visible smoke from ships, we see white smoke that clearly consists of for the most part condensed water vapour. In some of the pictures, we can also see smoke with a clear content of soot or other particles. This typically applies to ships starting up their engines in order to leave the port. In such situations, there are probably also elements of unburned hydrocarbons forming bluish smoke. The majority of $NO_x$ is in the form of NO out of the funnels. NO is a colourless gas, which is gradually converted to $NO_2$. Nevertheless, it will not be visible in the present concentrations.

## 5.3 Meteorology simulated with WRF

Wind roses depicting wind speeds and wind direction for the summer season of 2016 for the domains with 300-metre resolution for the Geirangerfjord and for the Aurlandsfjord/Nærøyfjord simulated with WRF are shown in Figure 7 and 8, respectively.

The modelled wind shows that the wind speed in general is relatively low in both fjord areas, mostly below 6.0 m/s during the modelling period. The wind directions in both calculation areas are mainly determined by the terrain; the wind follows the fjords and the coombes, as expected.

In the northwest of the calculation area for the Geirangerfjord, at Skagen, the prevailing wind direction is principally from south by southwest and towards the mountain areas to the north (Figure 7). Near Geiranger, the wind is mostly coming from northwest, i.e. from the fjords and in towards the village. There is also some wind coming from the opposite direction blowing out of the fjord. The prevailing wind direction in the Geirangerfjord thus indicates that emissions from the ship traffic in the fjord have a significant potential for being dispersed in the direction of the residential areas in Geiranger.

In the Nærøyfjord, the wind also mainly follows the terrain, but the prevailing wind direction is from land in the southwest and out over the fjord, which means that the inhabitants of Gudvangen in the innermost part of the Nærøyfjord and Nærøy are most likely not that exposed to emissions from the cruise traffic in the area. In Dyrdal further north, there is in addition a bit of wind from the northeast, which could disperse the air pollution towards the residences in this area.

As opposed to the Nærøyfjord, the prevailing wind direction at the fjord arm to the east, the Aurlandsfjord, is mainly from north by northeast from the fjord and directly towards Flåm at the end of the fjord. At Aurlandsvangen, the wind comes from both the northwest and the northeast, so that the village may periodically be exposed to air pollution from the ship traffic in the fjord.

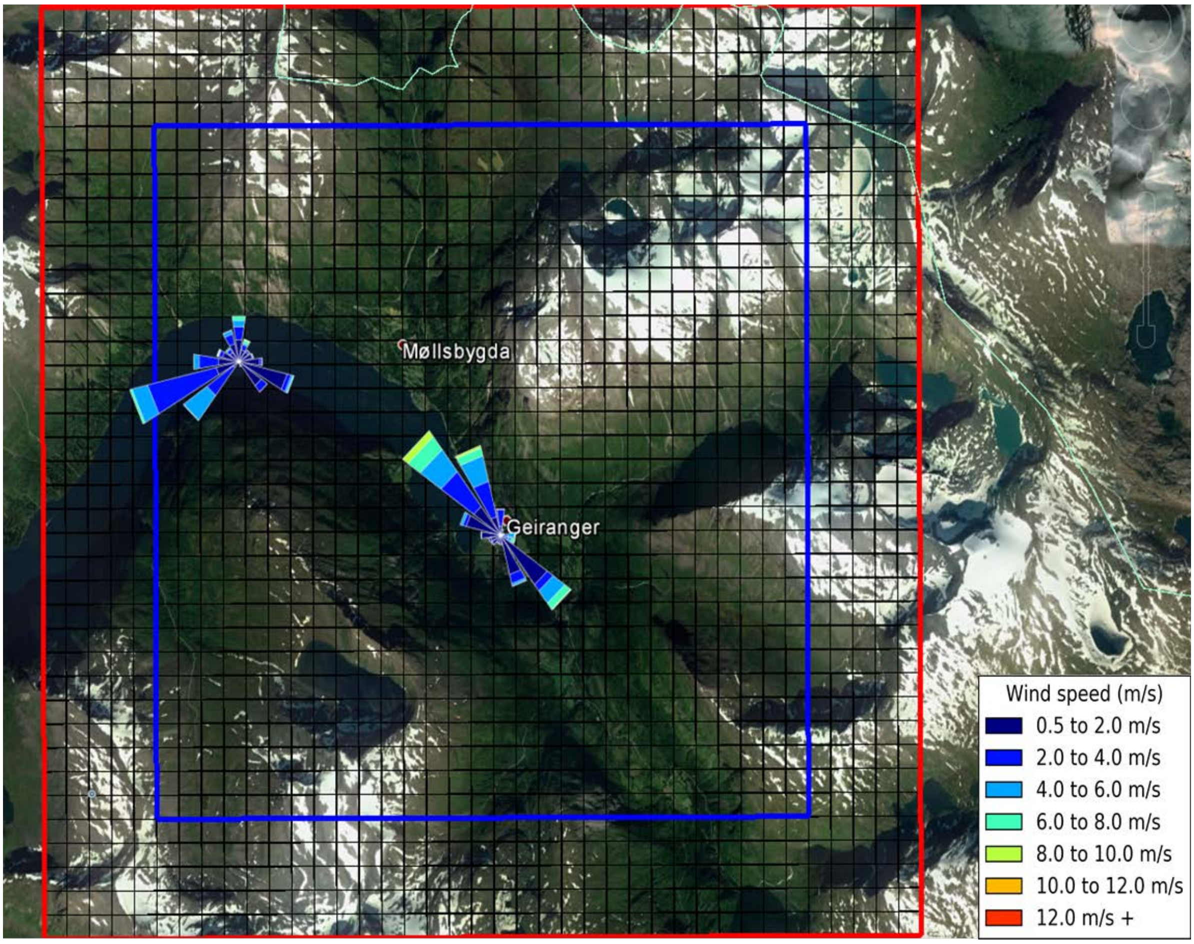


**Figure 7. Wind rose plot depicting the frequency distribution of wind speeds, and wind directions divided by sectors of 22.5° simulated with WRF, for the Geirangerfjord.**

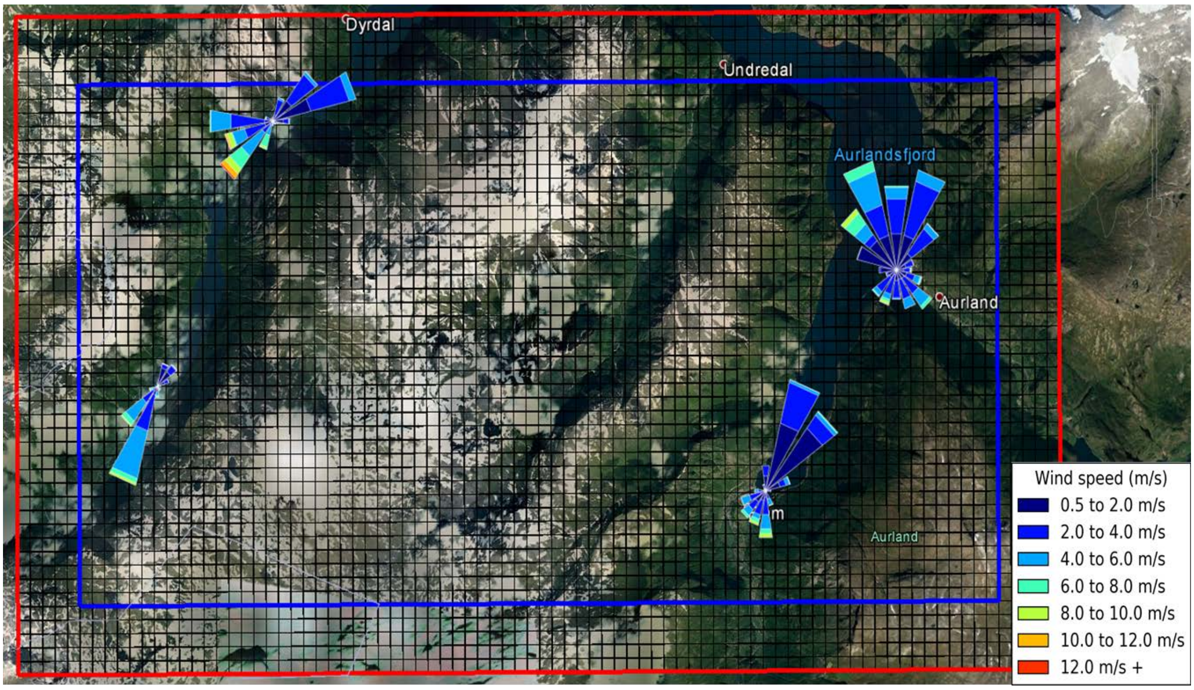


**Figure 8. Wind rose plot depicting the frequency distribution of wind speeds, and wind directions divided by sectors of 22.5° simulated with WRF, for the Nærøyfjord and Aurlandsfjord.**

## 5.4 Emissions to air in the world heritage fjords

### 5.4.1 Total emissions to air

Total calculated emissions of $NO_x$ from cruise and passenger ships, compared to other types of vessels that visited the fjords as well as road traffic on land in the areas in the period from June to August 2016, are presented in Table 6. Estimated emissions of $PM_{10}$, $PM_{2.5}$ and $SO_2$ from cruise and passenger ships and road traffic are also shown.

**Table 6. Emission of nitrogen oxides ($NO_x$), particulate matter ($PM_{10}$ and $PM_{2.5}$) and sulphur dioxide ($SO_2$) in tonnes for the period from June to August 2016 from cruise and passenger ships and road traffic, and of $NO_x$ for other vessels, in the selected fjord areas. The share of $NO_x$ emissions contributed by the various sources, out of the total $NO_x$ emissions, is indicated in per cent.**

| | The Geirangerfjord | | | | The Aurlandsfjord and Nærøyfjord | | | |
|---|---|---|---|---|---|---|---|---|
| | $NO_x$ | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ | $NO_x$ | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ |
| Cruise and passenger ships | 67.9 (81%) | 2.15 | 1.97 | 9.44 | 46.1 (84%) | 2.24 | 2.05 | 10.1 |
| Other vessels | 14.1 (17%) | | | | 4.8 (9%) | | | |
| Road traffic | 1.75 (2%) | 0.066 | 0.052 | | 3.7 (7%) | 0.25 | 0.19 | |

The emission estimates show that $NO_x$ is clearly dominant compared to the other examined components from shipping, whereas the emissions of particles and $SO_2$ are far smaller. Particularly $SO_2$ emissions from other sources will be insignificant since most smaller passenger ships use marine gas oil with a low sulphur content. Emissions of $SO_2$ from road traffic are more or less zero. In order to estimate the contribution to air pollution from other sources, such as other types of vessels than cruise/passenger ships, and vehicle traffic on the roads in the area, only the $NO_x$ emissions were therefore compared.

Table 6 shows that the emissions of $NO_x$ from road traffic and other vessels constituted a small percentage of the overall emissions: other vessels constituted 17% of the emissions in the Geirangerfjord and only 9% on the Aurlandsfjord/Nærøyfjord, while the corresponding numbers for road traffic were 2 and 7%. The dispersion modelling carried out in this study is therefore considered to give a sufficiently good indication of air quality in the areas in question for the period from June to August, even though only the emissions from vessels classified exclusively as cruise or passenger ships were included in these calculations. However, formation of clearly visible smoke clouds were also observed from certain other vessels that were not included in the calculations, and the road traffic in the area can in periods be high, as further discussed in *Part 6. Discussion and assessments.*

### 5.4.2 Emissions from cruise and passenger ships

Total emissions of $NO_x$, particulate matter ($PM_{10}$ and $PM_{2.5}$) and $SO_2$ from cruise and passenger ships in the period from June to August 2016 in the world heritage fjords calculated based on AIS data and IHS Fairplay registrations are listed in Table 7. The emission numbers are shown by engine type (propulsion machinery, auxiliary machinery and steam boilers).

**Table 7. Emissions (in tonnes) of nitrogen oxides ($NO_x$), sulphur dioxide ($SO_2$) and particulate matter ($PM_{10}$ and $PM_{2.5}$) from cruise and passenger ships in the summer months of June to August 2016 in the Geirangerfjord, the Aurlandsfjord in to Flåm and the Nærøyfjord.**

| | The Geirangerfjord | | | | The Aurlandsfjord / Nærøyfjord | | | |
|---|---|---|---|---|---|---|---|---|
| | $NO_x$ | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ | $NO_x$ | $PM_{10}$ | $PM_{2.5}$ | $SO_2$ |
| Propulsion machinery | 2.2 | 0.05 | 0.05 | 0.19 | 5.5 | 0.13 | 0.12 | 0.50 |
| Auxiliary machinery | 64.1 | 1.4 | 1.3 | 6.1 | 37.1 | 0.82 | 0.75 | 3.5 |
| Steam boilers | 1.7 | 0.26 | 0.24 | 1.3 | 3.5 | 0.56 | 0.51 | 2.7 |
| **In total** | **67.9** | **1.7** | **1.6** | **7.6** | **46.1** | **1.5** | **1.4** | **6.7** |

For the calculation areas, the overall emissions in the period were by far the highest from the auxiliary engines, which run in all types of operation modes. For example, the total emissions of $NO_x$ from auxiliary engines were 64.1 tonnes in the Geirangerfjord and 37.1 tonnes altogether in the Aurlandsfjord in to Flåm and in the Nærøyfjord. The propulsion engines are not in operation when the vessels are in port (hotel) and the steam boilers only operate during manoeuvring and hotel operation.

The emission data were used as input data for the CALPUFF dispersion modelling system. The emissions were formatted to contain hourly emission rates per grid cell for the period from June to the end of August. Figure 9, 10 and 11 show the overall modelled $NO_x$ emissions for the entire cruise season in the Geirangerfjord, Nærøyfjord near Gudvangen and the Aurlandsfjord near Flåm, respectively. These cell-aggregated emissions were converted to a CALPUFF input data format as time-varying point sources.

As presented in the Figures 9 to 11, the $NO_x$ emissions were the highest in the innermost parts of the fjords near the most common berths and anchorages for the cruise ships during the cruise ship season of 2016. The emissions do not exceed 0.2 tonnes for any of the 100-metre grid cells in the outermost parts of the fjord arms, and reach their maximum of between 20 and 50 tonnes in some locations near Geiranger and Flåm. In the Nærøyfjord, the emissions were low throughout, and no grid cells had emissions above 0.2 tonnes. The emission profiles, i.e. distribution of emissions with time and place, for $SO_2$ and particulate matter ($PM_{10}$ and $PM_{2.5}$) in the three fjords were about the same as for $NO_2$, with somewhat lower levels. The emission maps for these components are therefore not included.

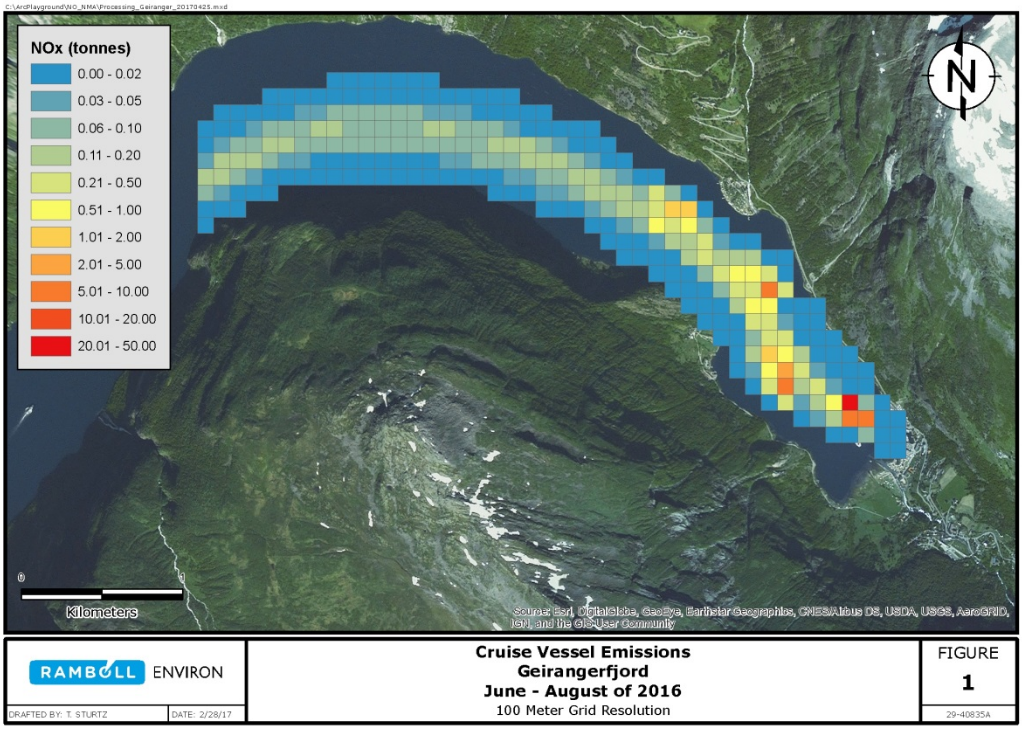


**Figure 9. Calculated total emissions of nitrogen oxides ($NO_x$) in tonnes, in the Geirangerfjord for the cruise ship season of 2016 (from 1 June to 31 August).**

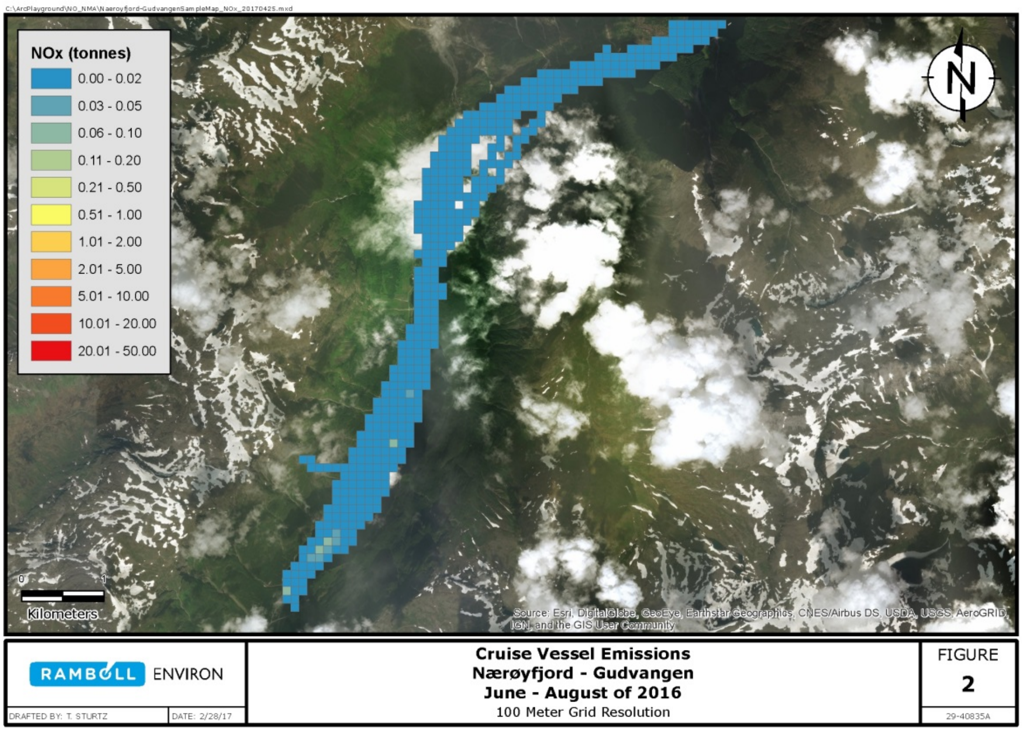


**Figure 10. Calculated total emissions of nitrogen oxides ($NO_x$) in tonnes, in the Nærøyfjord to Gudvangen for the cruise ship season of 2016 (from 1 June to 31 August).**

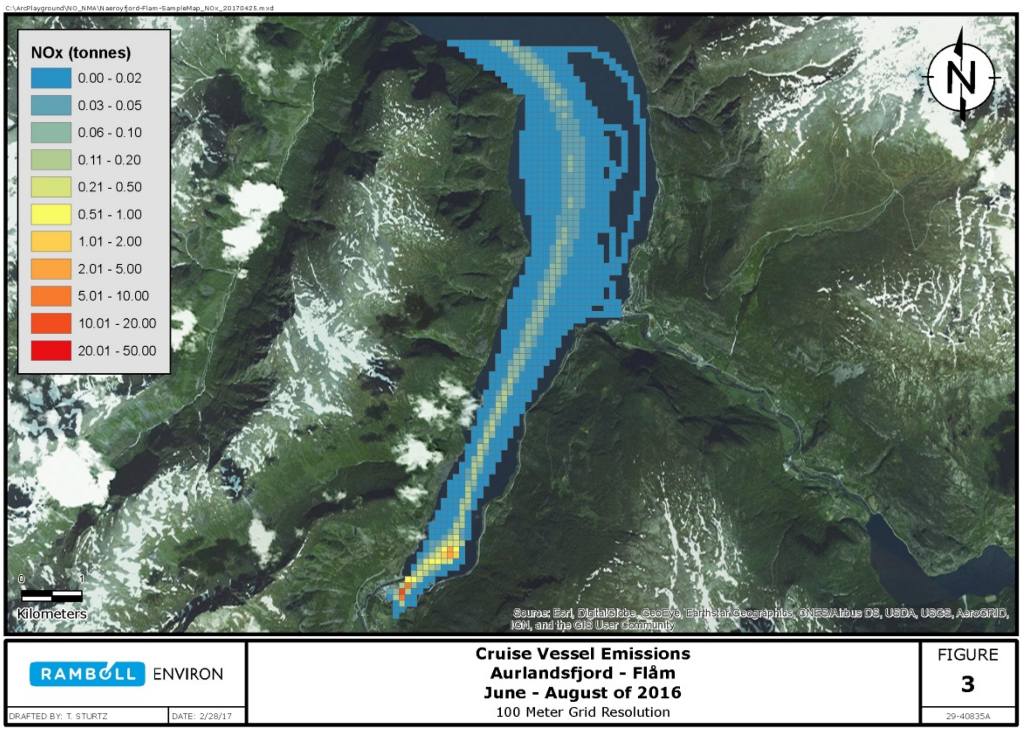


**Figure 11. Calculated total emissions of nitrogen oxides ($NO_x$) in tonnes, in the Aurlandsfjord to Flåm for the cruise ship season of 2016 (from 1 June to 31 August).**

## 5.5 Dispersion of air pollution from cruise traffic in the fjord areas in question

Maps showing the dispersion of $NO_2$, $SO_2$ and $PM_{2.5}$ are shown in Figure 12, 13 and 14, respectively, for the Geirangerfjord, and in Figure 15, 16 and 17, respectively, for the Aurlandsfjord near Flåm. The dispersion maps are presented in a larger format in Appendix 6.

The modelled pollutants were mostly below the action limit values given as daily mean ($SO_2$ and $PM_{10}$) or hourly mean ($SO_2$ and $NO_2$) for outdoor air in the Pollution Regulations. Concentrations of $NO_2$ exceeded the hourly limit value of 200 µg/m$^3$ for only one hourly period within two smaller, uninhabited areas in the mountainside on the northeast side of the Geirangerfjord, and in the Aurlandsfjord near Flåm. Few areas had $NO_2$ concentrations just under the hourly limit value; in most places, the concentrations were below 170 µg/m$^3$.

Since the levels of relevant substances in the air were modelled only for a time period of a few months, the levels could not be related to the action limit values having a calendar year as mean time, or maximum number of exceedances of the daily limit values in the course of a calendar year. The alert classes given on luftkvalitet.info are presented as hourly means for all the examined components, and provides the lower limits for pollution levels related to health risks. Modelling of exceedances of at least one hour during the calculation period of the lower limits for the alert classes developed by the Norwegian Institute of Public Health, the Norwegian Public Roads Administration and the Norwegian Environment Agency are therefore considered the most relevant limits by which to assess the dispersion in the fjord areas. The alert classes are indicated by colour codes: orange (moderate level of pollution and health risk), red (high level of pollution, significant health risk) and purple alert class (very high level of pollution, serious health risk). In city areas, these limits are used to alert the population when the air pollution reaches a level considered to pose a health risk for exposed groups, or the entire population. However, we would like to underline that these limits are not legally binding action limit values.

It was mainly $NO_x$ that was present in concentrations that exceeded the alert classes given as hourly mean in short periods at Geiranger and Flåm. In the Geirangerfjord, the lower limit for the orange alert class was exceeded at least once in a relatively large area that covered most of Geiranger, the area northeast of the Geirangerfjord including Ørnevegen and the mountainside southwest of the fjord up to Skagen (Figure 12). Emissions from cruise ships in the fjord have in other words lead to moderate levels of $NO_2$ in these areas over short periods of time, which corresponds to a moderate health risk. A moderate health risk means that harmful health effects could occur in people with existing respiratory diseases such as asthma or cardiovascular disease. The concentrations exceeded the lower limit for red alert class in a small area on the northeast side of the fjord at the foot of the mountain Sætertverrfjellet, corresponding to the area where the limit value in accordance with the Pollution Regulations was exceeded, but there are no residences in this zone.

At Flåm in the innermost part of the eastern arm of the Aurlandsfjord, the concentrations of $NO_2$ also exceeded the lower limit for orange alert class in a larger area south of the fjord over the majority of the village, and parts of the mountainsides south, east and west of the fjord (Figure 15). $NO_2$ levels corresponding to red alert class occurred in a small area out in the fjord northeast of Flåm. None of the areas around the Nærøyfjord were exposed to elevated concentrations of any of the substances examined in this study.

Elevated levels of $SO_2$ and $PM_{2.5}$ would occur only within small areas out in the Aurlandsfjord near Flåm, and in the mountainside northwest of Geiranger. The area in the Aurlandsfjord where the orange alert classes for $SO_2$ and $PM_{2.5}$ were exceeded was close to one of the cruise ships in the fjord. The exceedances of the orange and, for $PM_{2.5}$, red alert classes in a small area on the southwest side of the mountain Sætertverrfjellet in Geiranger were most likely caused by emissions from a cruise ship further northwest in the fjord near Skagen, which spread by northwesterly winds.

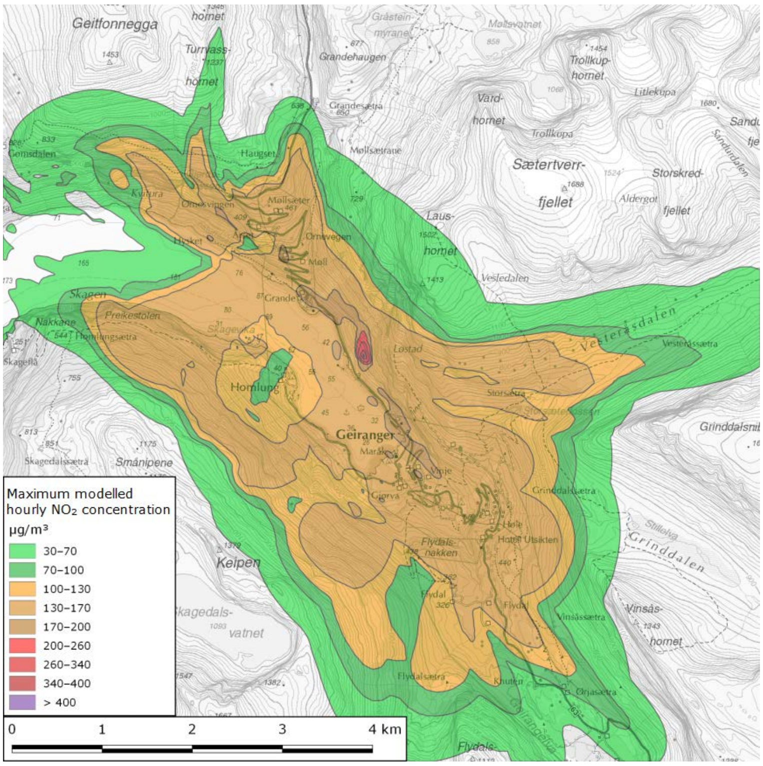


**Figure 12. Dispersion maps showing modelled concentrations of nitrogen dioxide ($NO_2$) emitted from cruise and passenger ships in the area near Geiranger during the period from 1 June to 31 August 2016. The dispersion is illustrated by colour codes corresponding to at least one exceedance of the various alert classes for air quality given as hourly means, developed by the Norwegian Institute of Public Health, the Norwegian Public Roads Administration and the Norwegian Environment Agency.**

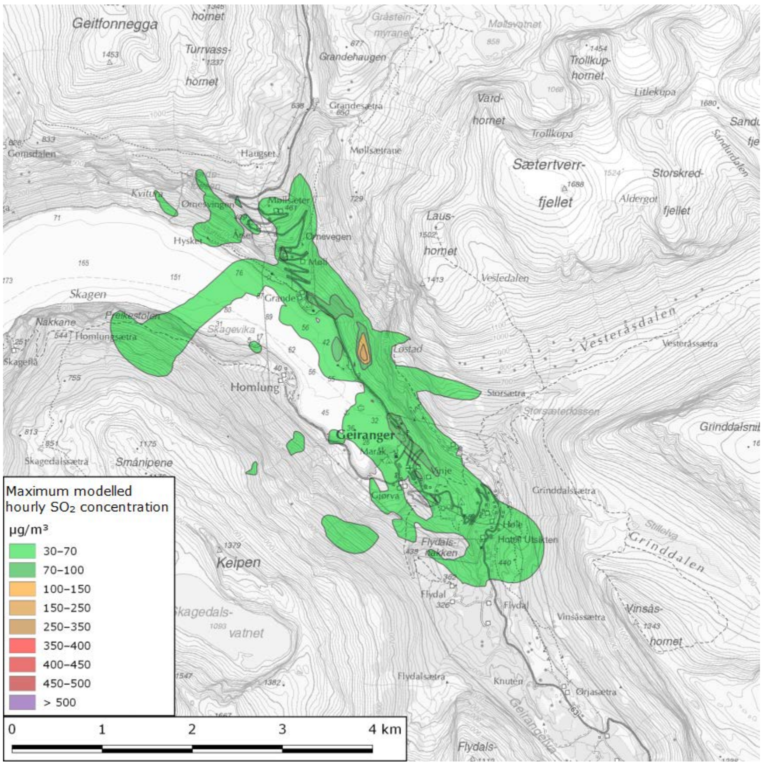


**Figure 13. Dispersion maps showing modelled concentrations of sulphur dioxide ($SO_2$) emitted from cruise and passenger ships in the area near Geiranger during the period from 1 June to 31 August 2016. The dispersion is illustrated by colour codes corresponding to at least one exceedance of the various alert classes for air quality given as hourly means, developed by the Norwegian Institute of Public Health, the Norwegian Public Roads Administration and the Norwegian Environment Agency.**

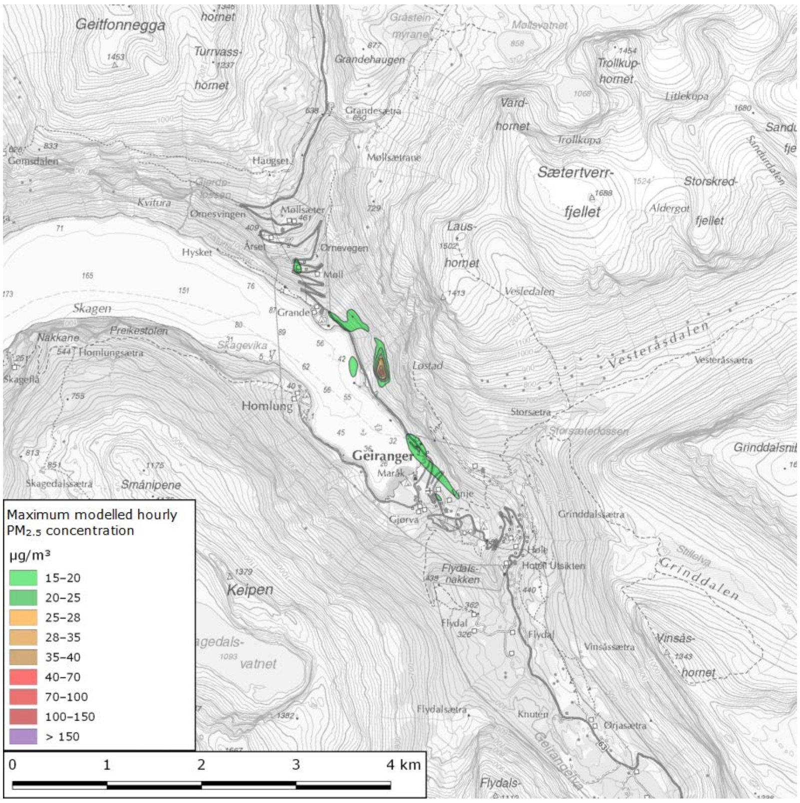


**Figure 14. Dispersion maps showing modelled concentrations of particulate matter ($PM_{2.5}$) emitted from cruise and passenger ships in the area near Geiranger during the period from 1 June to 31 August 2016. The dispersion is illustrated by colour codes corresponding to at least one exceedance of the various**

**alert classes for air quality given as hourly means, developed by the Norwegian Institute of Public Health, the Norwegian Public Roads Administration and the Norwegian Environment Agency.**

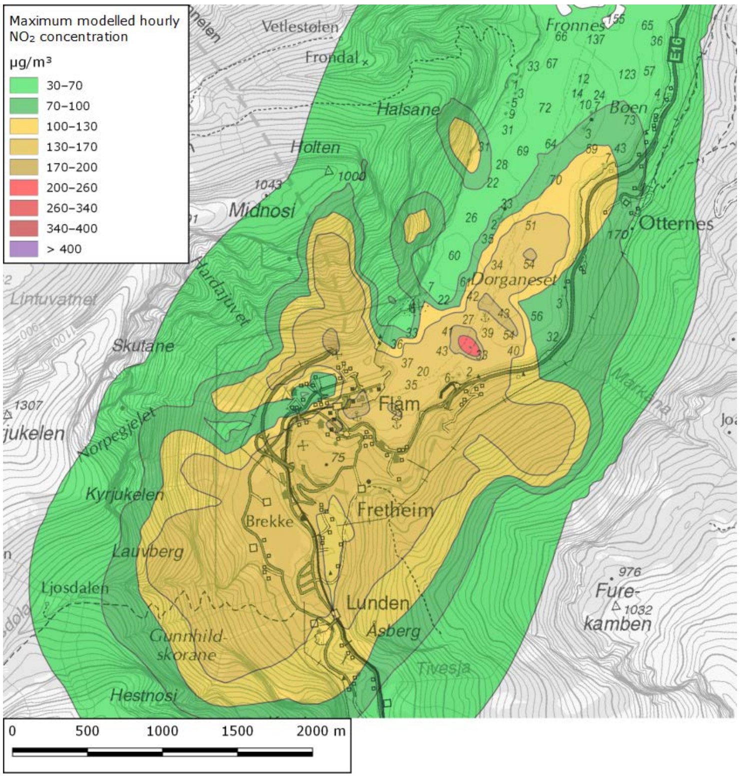


**Figure 15. Dispersion maps showing modelled concentrations of nitrogen dioxide ($NO_2$) emitted from cruise and passenger ships in the area near Flåm at the end of the Aurlandsfjord during the period from 1 June to 31 August 2016. The dispersion is illustrated by colour codes corresponding to at least one exceedance of the various alert classes for air quality given as hourly means, developed by the Norwegian Institute of Public Health, the Norwegian Public Roads Administration and the Norwegian Environment Agency.**

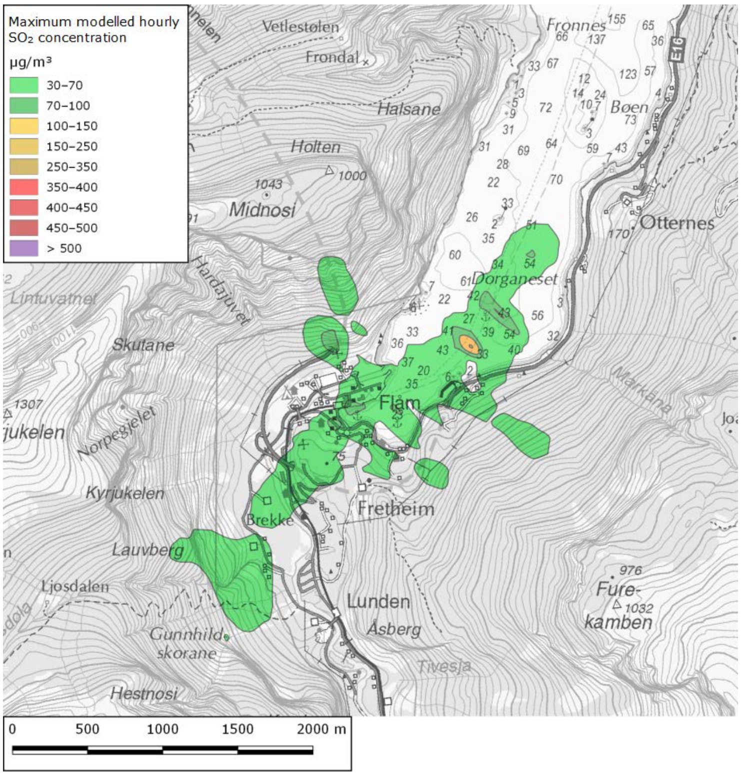


**Figure 16. Dispersion maps showing modelled concentrations of sulphur dioxide ($SO_2$) emitted from cruise and passenger ships in the area near Flåm at the end of the Aurlandsfjord during the period from**

**1 June to 31 August 2016. The dispersion is illustrated by colour codes corresponding to at least one exceedance of the various alert classes for air quality given as hourly means, developed by the Norwegian Institute of Public Health, the Norwegian Public Roads Administration and the Norwegian Environment Agency.**

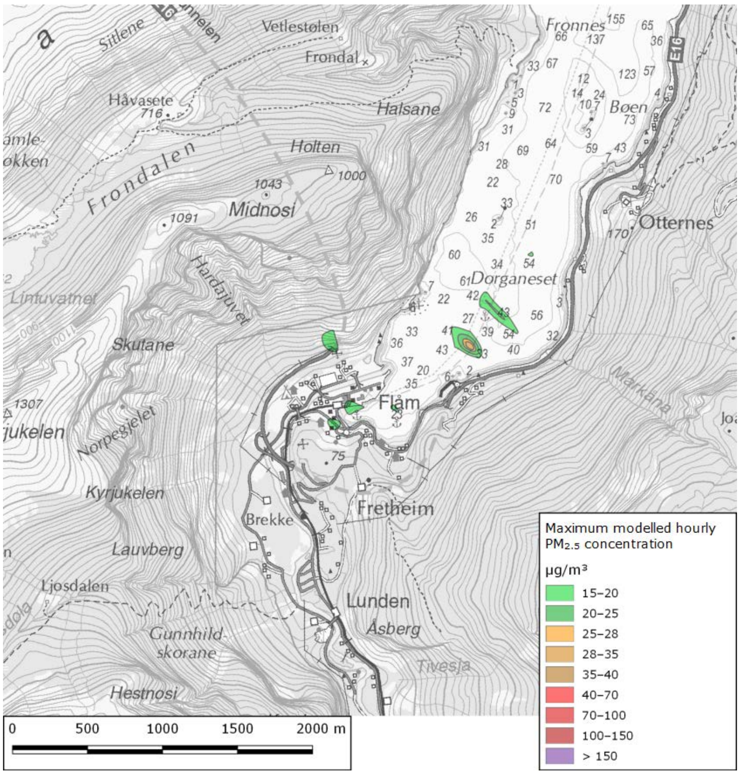


**Figure 17. Dispersion maps showing modelled concentrations of particulate matter ($PM_{2.5}$) emitted from cruise and passenger ships in the area near Flåm at the end of the Aurlandsfjord during the period from 1 June to 31 August 2016. The dispersion is illustrated by colour codes corresponding to at least one exceedance of the various alert classes for air quality given as hourly means, developed by the Norwegian Institute of Public Health, the Norwegian Public Roads Administration and the Norwegian Environment Agency.**

The concentrations of $PM_{10}$ were low throughout, far below both the limit values pursuant to both the Pollution Regulations and the alert classes. A dispersion map for $PM_{10}$ is therefore not presented in this report. Measurements taken in the Geirangerfjord, however, showed elevated concentrations of fine particles, particularly in the port area; this is further discussed in the section on Discussion and assessments.

# 6. DISCUSSION AND ASSESSMENTS

## 6.1 Meteorological modelling

A quantitative analysis of the WRF simulations for 2016 indicated that WRF simulated temperature, air humidity and wind speed accurately in the fjord areas in question, when the simulations were compared to available meteorological measurement data. Skewness and errors associated with modelled monthly average variables were well within established METSTAT standards for complex terrain. A limitation in the evaluation is the lack of complete meteorological data within the WRF modelling domains with 300-metre resolution in the Geirangerfjord and the Nærøyfjord/Aurlandsfjord. In addition, the evaluation of the wind direction simulated by WRF indicated some divergence from available observations, particularly in the Geirangerfjord domain. Wind direction is very difficult to model accurately in complex mountain terrains. This was particularly the case for the gird cells with lower resolution, which were the only ones that had sufficient observations from weather stations for the analysis. Due to this, a qualitative analysis was also carried out of WRF simulated winds within the 300-metre grid. The WRF wind roses in the fjords seem to correspond well with the local mountain terrain.

The fact that there are so few complete meteorological stations in the Norwegian fjord areas makes it necessary to use meteorological modelling with WRF in order to get representative dispersion conditions for use in air quality modelling.

## 6.2 Emissions to air and discharges to sea in fjord areas from cruise ships

The methods used in this study provide good and exact estimates for emissions and discharges based on actual ship movements from AIS data and information on each ship from the IHS Fairplay database and the completed survey. During the summer months of June, July and August 2016, the emissions were the highest in the fjords outside Geiranger and Flåm. Emissions of $NO_x$ from cruise and passenger ships were clearly predominant.

The pictures from the video monitoring of the Geirangerfjord showed that vessels travelling in the fjord periodically cause formation of easily observable smoke clouds that would form over large parts of the fjord. Visible smoke clouds occurred in various weather conditions, from various types of vessels and both upon arrival and departure. It is difficult to use this type of pictures to say anything about the content or concentrations of the smoke clouds observed. However, the pictures could indicate that there may be episodes with high emissions from individual ships caused by operational conditions when arriving or departing. Such episodes cannot be made out by the method used for calculation of emissions, which used average emission factors, and could have led to an underestimate of emissions for shorter periods.

Discharges to sea are a limited problem when it comes to the cruise ships, since almost none of them declared any discharge of untreated or untreated sewage or grey water in the world heritage fjord, nor any discharge in connection with scrubber systems. Other vessels, however, routinely discharge treated sewage and grey water in the fjord areas, along with small amounts of bilge water if applicable.

## 6.3 Assessment of dispersion of air pollution and local air quality in the fjord areas

The dispersion calculations carried out for the three fjords for the summer months of June to August in 2016 mainly indicated low concentrations of $SO_2$, $PM_{10}$ and $PM_{2.5}$. The action limit values of chapter 7 of the Pollution Regulations were exceeded in small, uninhabited areas in the Geirangerfjord and the Aurlandsfjord. The levels of $SO_2$ and $PM_{10}$ were well below the action limit values. $NO_2$ concentrations were at times elevated in Geiranger and Flåm. This may periodically constitute a moderate health risk according to the air quality criteria.

The calculations that were performed in this project were limited to vessels classified as cruise or passenger ships, which clearly dominated with regard to emission of air pollution in the period from June to August in the world heritage sites. The video monitoring of the Geirangerfjord, however, showed that several smaller combination type vessels engaged in regular service, like certain cruise and passenger ships, had emissions that generated visible smoke clouds. The emission calculations that compared the contribution from cruise and passenger ships to the contribution from other vessels showed that the emissions from the former are clearly predominant in the areas during the summer period, but that the contribution from some of the remaining vessels could mean that the dispersion is somewhat larger than the calculations performed in this study indicate.

Since the emissions of air polluting components from vehicles on the roads in the fjord areas only constituted a small percentage of the emissions compared to the cruise ships that visited the fjords in the summer period, the road traffic emissions have not been included in the dispersion calculations. In these areas, however, there are large seasonal traffic fluctuations on the roads, with far more traffic in the tourist season in the summer months compared to the winter period. Particularly when tourists from the cruise ships or other passenger ships arrive in the port, there are many buses in operation. In this study, the available seasonal numbers for weekly emissions were used in the emission calculations. It is nevertheless possible that the traffic in short periods will be so heavy that it could have a negative impact on the air quality.

It is important to be aware of uncertainties connected with modelling of local air quality and assumptions made in the calculations:

- Meteorological conditions vary between seasons and years, and meteorology measured at a measuring station could deviate from the conditions in surrounding areas.
- Emissions factors used in the emission calculations are average numbers, and will depend on conditions such as operational profile. There are also some uncertainties related to the vessel information registered in the Fairplay database.
- The distribution between NO and $NO_2$ in the air varies depending on meteorological conditions and atmospheric composition.
- In the dispersion modelling, only emissions from cruise and passenger ships were included, since these are very predominant with regard to the total emissions in the areas in the summer. Other types of vessels, small craft, road traffic and other sources of emissions are therefore not included in the dispersion calculations.

For verification of modelled concentrations, measurements can be carried out, as described in the below paragraph. Measurements provide actual concentrations for a given time, but only for the location of the measuring instruments, and are also associated with some uncertainty. Dispersion calculations provide a picture of the dispersion within a larger area, and can identify specific areas that will be exposed to reduced air quality. Such calculations provide the most exact results over longer periods of time. In other words, measurements and dispersion modelling provide different types of information about the air quality in an area, and can be used to verify and complement each other.

## 6.4 Measurements in the Geirangerfjord area

A comprehensive measuring programme was initiated in the Geirangerfjord in 2016. The project is financed by the foundation Stiftinga Geirangerfjorden Verdsarv, and is coordinated by Professor Jörg Löffler's research group. Equipment for measuring a number of meteorological parameters and air pollutants ($NO_x$, $SO_2$, $PM_{10}$, $PM_{2.5}$ and ozone) has been set up permanently in three different locations near the Geirangerfjord for continuous monitoring over a period of 30 years.

The first annual report for the measurements in the Geirangerfjord area for 2016 has been presented, with results reported for the period from May 2015 to September 2016 for two stations: at the port area and at the fjord centre higher up the mountain.[39] The $SO_2$ levels were low throughout the period. The concentrations of $PM_{10}$ as daily mean were below the limit value of 50 $\mu g/m^3$ for the entire period covered by the report. The levels of the size fraction $PM_{1-2.5}$ were somewhat elevated, particularly in the summer period, even though the annual mean did not exceed the action limit value of 15 µg/m$^3$. Relatively high concentrations of $PM_1$ were measured for parts of the time period; but there are no limit values for this size fraction. Due to lack of $NO_x$/$NO_2$ data and low levels of the remaining examined components it was not possible to validate the results from the dispersion modelling through the measurements.

The Norwegian Public Health Institute has made a statement regarding the measurements carried out in the Geirangerfjord, which is available through Stiftinga Geirangerfjorden Verdsarv. The letter specifies that the measured levels of $PM_{2.5}$ and $PM_1$ are elevated in the area, and that they, when assessed against the air quality criteria, could lead to aggravation of disease in vulnerable population groups.

There have also been previous measurements of the air pollution in the Geirangerfjord. The Norwegian Institute for Air Research (NILU) measured concentrations of $PM_{10}$ and $NO_2$ during parts of the 2010 cruise season.[40] The limit value for the $NO_2$ hourly mean was not exceeded during the measuring period, but the $PM_{10}$ daily mean requirement was exceeded twice. Since the margin of tolerance permits the daily mean to be exceeded up to 35 times a calendar year, and it is assumed that the highest levels occurred in the measuring period, it was concluded that the number of exceedances for both $NO_2$ and $PM_{10}$ was not higher than permitted for the year.

Measurements taken at Geiranger thus indicate that the concentrations of particulate matter, particularly in the port area, could at times be problematic. Levels measured at the pier could be assumed to be caused, to a large extent, by other emission sources than cruise ships, such as small and medium vessels at berth and car and bus traffic, which were not included in the calculations carried out in this study.

### 6.5 Proposed mitigating measures

Since seagoing vessels could cause significant emissions to air in the world heritage fjords, which could pose a risk to people's health and the natural environment and which from time to time cause formation of undesirable smoke clouds above the areas, it is important to consider possible measures in order to reduce such emissions. A number of measures have been implemented both internationally, regionally and nationally, and emission limits and other restrictions are continuously made more stringent. The legislation for reduction of emissions from shipping and rules on energy efficiency for vessels have become stricter through MARPOL. The more stringent rules for sulphur content of fuel within the EU/EEA are examples of special regional requirements. Individual US states, such as California, have also introduced stricter requirements for emissions and pollution-reducing technology in ports.

The main purpose of the measures will be to reduce the emissions from various types of vessels. Stricter requirements for emission-reducing technology may be implemented, e.g. that all ships must satisfy the Tier II or Tier III requirements with regard to $NO_x$ emissions. The requirements for sulphur content of fuel may also be made even more stringent, so that the sulphur content must be less than 0.1% in all fjord areas, even outside the ECAs. A prohibition against heavy fuel oil could be adopted if possible, so that all vessels may only use marine diesel oil, for example. Emission limits may additionally be set up, which all or some vessels must comply with. In order to satisfy such requirements, several older ships may possibly have to upgrade engines and retrofit necessary pollution-reducing technology such as exhaust gas recirculation (EGR) systems or selective catalytic reduction (SCR) in order to reduce $NO_x$ emissions. Scrubber systems are primarily designed to reduce the $SO_x$ emissions, but also contribute to removing particles from exhaust gas. With regard to discharges to sea, a possible measure could be to adopt a prohibition against discharge of both treated and untreated sewage near the fjords.

Ship traffic limitations are measures that have been introduced for example in fjord areas near Glacier Bay national park in Alaska. In Glacier Bay, a limit of maximum two cruise ships per day has been laid down, along with a seasonal limit. Cruise ships wishing to visit the area must apply for access and document environmental measures that they have implemented. This if a very effective measure, which both limits the ship traffic significantly and makes sure that only ships with proper emission-reducing technology are given access. This could basically also be desirable for most fjord areas in Norway with high levels of tourism. There are nevertheless large differences between fjord areas in Norway and in Alaska with regard to preconditions such as current legislation, population, types of nature and tourism. Working to reduce the emissions and discharges from existing ship traffic is probably more likely and desirable in Norway. A measure of current interest could be to work towards expanding the current emission control areas to include sea and fjord areas north of the existing boarder. Today's ECA in the North Sea goes up to 62°N, and thus includes the Aurlandsfjord and the Nærøyfjord, but not the Geirangerfjord.

Reporting requirements for technical features on the ships significant for emission and discharge could also be introduced. It would have to be determined which types of vessels that should be covered by such requirements, which bodies to report to, and whether the administration of such a regime would be justifiable compared to the utility value.

For all relevant measures, the potential utility value and the possible negative consequences would need to be weighed. The goal of the measures is to reduce the emissions and discharge, which could reduce the risk of harmful effects on health and negative effects on the nature in the areas, and could limit the formation of visible smoke clouds. Measures such as setting up shore power facilities could also stimulate the local industry and provide local job opportunities. However, such measures will also include considerable investments, and it would have to be decided who these costs will be covered by. There will generally be many questions related to the implementation of various measures related to legal bases, responsible authorities, to which areas and which types of vessels the requirements would apply, measurement and assessment of effects, and control of and sanctions for violation of the rules. There are many interested parties involved: Local residents in the fjord areas, tourists, vessel owners, local industry and local, national and international authorities.

Based on the surveys carried out as part of this study, the problems related to pollution and effects on the local air quality in these areas are considered to involve a certain elevated risk of damage to health in certain periods.

One of the main problems in the areas is the formation of larger amounts of visible smoke for shorter periods. The formation of smoke when cold-starting engines is an issue that particularly pertains to older engines with poor regulation. For vessels using scrubber systems, measures could be implemented to pass the exhaust through a heat exchanger or dryer after the scrubber, to ensure that the water vapour is not visible. Dialogues focusing on operational measures such as revised procedures when cold-starting engines, specific preparations before departure and general awareness with regard to emissions could help mitigate the problem with formation of smoke clouds in the areas in question.

# 7. CONCLUSION

The mapping of emissions to air and discharges to sea from ships in the world heritage fjords the Geirangerfjord, Aurlandsfjord and Nærøyfjord for the period indicated that the air quality, particularly around Geiranger and Flåm, could from time to time be problematic, and could possible cause somewhat increased risk of damage to health.

The calculated emissions during the summer months from June to August 2016 were the largest for $NO_x$ and the highest in the areas near Geiranger and Flåm where cruise ships were regularly in port. The dispersion calculations conducted with CALPUFF also showed generally higher concentrations and the largest dispersion of $NO_2$ compared to $SO_2$, $PM_{2.5}$ and $PM_{10}$. At times, large parts of the areas in the Geirangerfjord, including Geiranger, and Flåm in the Aurlandsfjord had $NO_2$ levels that could be classified as moderate and constitute a moderate health risk according to the alert classes. The levels of $SO_2$ and $PM_{10}$ were well below the applicable action limit values in outdoor air laid down in chapter 7 of the Pollution Regulations, whereas the $NO_2$ concentrations exceeded the time limit value over a short period of time in smaller uninhabited places. For most of the time and for the majority of places in the world heritage fjords, the concentration of the examined components were well below the limit values pursuant to the Pollution Regulations.

The emission calculations carried out in the study showed that the cruise and passenger ships clearly dominated with regard to emissions to air in the summer months of June to August in the world heritage areas. Pictures taken with the installed GoPro camera of the Geirangerfjord showed that visible smoke clouds were also formed by certain other combination type ships engaged on a regular service. Since only emissions from cruise and passenger ships were included in the dispersion modelling, the dispersion of air pollution in the areas is probably somewhat larger than what the calculations show.

It is primarily ferries and Hurtigruten's ships, in addition to certain cruise ships, that discharge treated sewage and grey water into the sea in the world heritage fjords. According to the survey, most vessels travelling in the fjords do not discharge bilge water and substances from scrubber systems.

A number of measures for reducing emissions to air and discharges to sea from cruise ships and other vessels calling at the world heritage fjord and other fjord areas in Norway can potentially be implemented. Measures may be directed at more stringent requirements for emission and discharge, pollution-reducing technology, engine type and operation on all ships, or limitations could be introduced in the number of ships that get to visit certain defined areas. An expansion to the north of the ECAs as well as introduction of more special requirements for such areas could be considered in order to include more fjord areas and adapt the emission/discharge regulations thereto. Development of shore power in the fjord areas would also contribute to reducing the emissions to air significantly.

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