ACCESS
Arctic Climate Change
Economy and Society

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ACCESS

Arctic Climate Change, Economy and Society

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Introduction

Currently, the Arctic produces about a tenth of the world's oil and a quarter of its gas (AMAP: Arctic Oil and Gas 2007). In addition, the Arctic still has large undeveloped oil and gas reserves; 30% of the world's undiscovered gas, and 13% of the world's undiscovered oil are predicted to be north of the Arctic Circle (Gautier et al., 2009), with most reserves located under the Arctic Ocean floor. Compared to the rest of the world, warming is proceeding twice as fast in the Arctic and the Arctic Ocean is projected to become nearly ice-free in summer within this century (Barnett et al., 2014)**).** The decline of Arctic sea ice is expected to open the possibilities for hydrocarbon extraction in the Arctic, which will increase emissions of atmospheric pollutants. Major emission sources are combustion of natural gas in turbines, flaring of natural gas, and combustion of diesel in diesel engines, resulting in a broad emissions mix of short-lived climate forcers & their precursors (NO_x, SO_x, VOCs, BC). Type and volume of emissions depends both on the combustion technology and fuel consumption (FACTS 2014).

The landscape of Arctic oil/gas extraction is changing rapidly. Major Arctic oil/gas extraction activities are planned in the near future in the US and Canadian Arctic. Russia has a large expanse of Arctic territory with significant oil/gas reserves, which has recently included development of the Prirazlomnaya platform in the Pechora Sea as well as extraction in the region of the Ob valley, for example, which have been estimated to be an important source of Arctic black carbon (BC) (Stohl et al., 2013), which typically warms the Atmosphere (Bond et al., 2013). Also Norwegian activities continuously migrate northwards. Two examples include facilities in the Barents Sea (Norway), the operating field (Snøhvit), and ongoing development of another field (Goliat). In our study, we focus on operating oil/gas platforms in the Norwegian Sea, which are south of the Arctic Circle, as a proxy for offshore oil/gas development farther north in the Arctic in the future.

Atmospheric emissions from oil and gas extraction in the Arctic are a concern because of their influence on air quality and climate. Short-lived pollutants (including O_3, BC) are

particularly important because they contribute to Arctic climate change (e.g. Quinn et al., 2008) and include species that make up air pollution (Law and Stohl, 2007; Law et al., 2014). BC is produced from incomplete combustion of fossil fuels and biofuels, which occurs during the oil/gas extraction process. Recent publications have identified oil/gas production and exploration as a potentially significant source of Arctic BC and highlighted the need to better quantify emissions from these activities (Odemark et al., 2012, Peters et al., 2011, Quinn et al., 2008, Stohl et al., 2013). A particular focus has been placed on flaring in Russia, a way of discharging and disposing of gaseous and liquid hydrocarbons through combustion, which is estimated to be a major source of BC surface concentrations in the Arctic (Stohl et al., 2013). However, the magnitude and characteristics of emissions from flaring are highly uncertain. In addition, venting of gases during the extraction process is also an important source of emissions to air, contributing to air pollution formation.

Knowledge of the type, amount, location, and temporal cycle of emissions from oil/gas exploration and production is essential to correctly predict their current impacts on Arctic air quality and climate. However, there is little or no consistency between current emission datasets, especially with respect to emissions in the Norwegian Sea. For example, gridded emissions datasets provided by EDGAR (The Emissions Database for Global Atmospheric Research - http://edgar.jrc.ec.europa.eu/) and TNO-MACC (Netherlands Organisation for Applied Scientific Research TNO European Emissions developed for the Monitoring Atmospheric Composition and Climate project, details found in: Kuenen et al., 2014; Denier van der Gon et al., 2005; Denier van der Gon et al., 2010) have no emissions of SO_2 over the Norwegian Sea linked to hydrocarbon extraction, while certain inventories were found to include shipping emissions in the same category. There are several reported measurements of emissions from on-shore hydrocarbon extraction facilities: Prudhoe Bay, Alaska (Jaffe et al. 1995; Brooks et al., 1997; Brock et al., 2011), Denver-Julesburg Basin in Colorado (Pétron et al., 2014), natural gas and oil production field in Uintah County, Utah (Karion et al., 2013), Agri Valley, Italy (Pavese et al. 2012). In this deliverable we present the first measurements of extraction activities in the Norwegian Sea, adding to the number

of in-situ measurements with the goal of more fully understanding emissions from hydrocarbon exploration and extraction activities.

In order to meet this goal, an aircraft campaign based in northern Norway was conducted in July 2012, as part of the EU ACCESS (Arctic Climate Change Economy and Society) project (Roiger et al., 2014). During the campaign, two of the flights focused on measuring emissions from oil/gas platforms, drilling rigs, and tankers in the Norwegian Sea with the objective to characterize and quantify emissions and their impacts. While these installations are south of the Arctic Circle, they are considered within the geographical Arctic by AMAP (Arctic Monitoring and Assessment Programme). AMAP created the, so-called, *AMAP ar*ea as the territory for carrying out environmental monitoring under the Arctic Environmental Protection Strategy. The area was defined on regional extent and includes areas north of the Arctic Circle (66°32'N), and north of 62°N in Asia, and 60°N in North America, with modifications to include important marine areas (for example, the Norwegian Sea). Due to the AMAP definition and the use of this boundary for Arctic environmental monitoring, the probed facilities and their emissions are often considered within the Arctic.

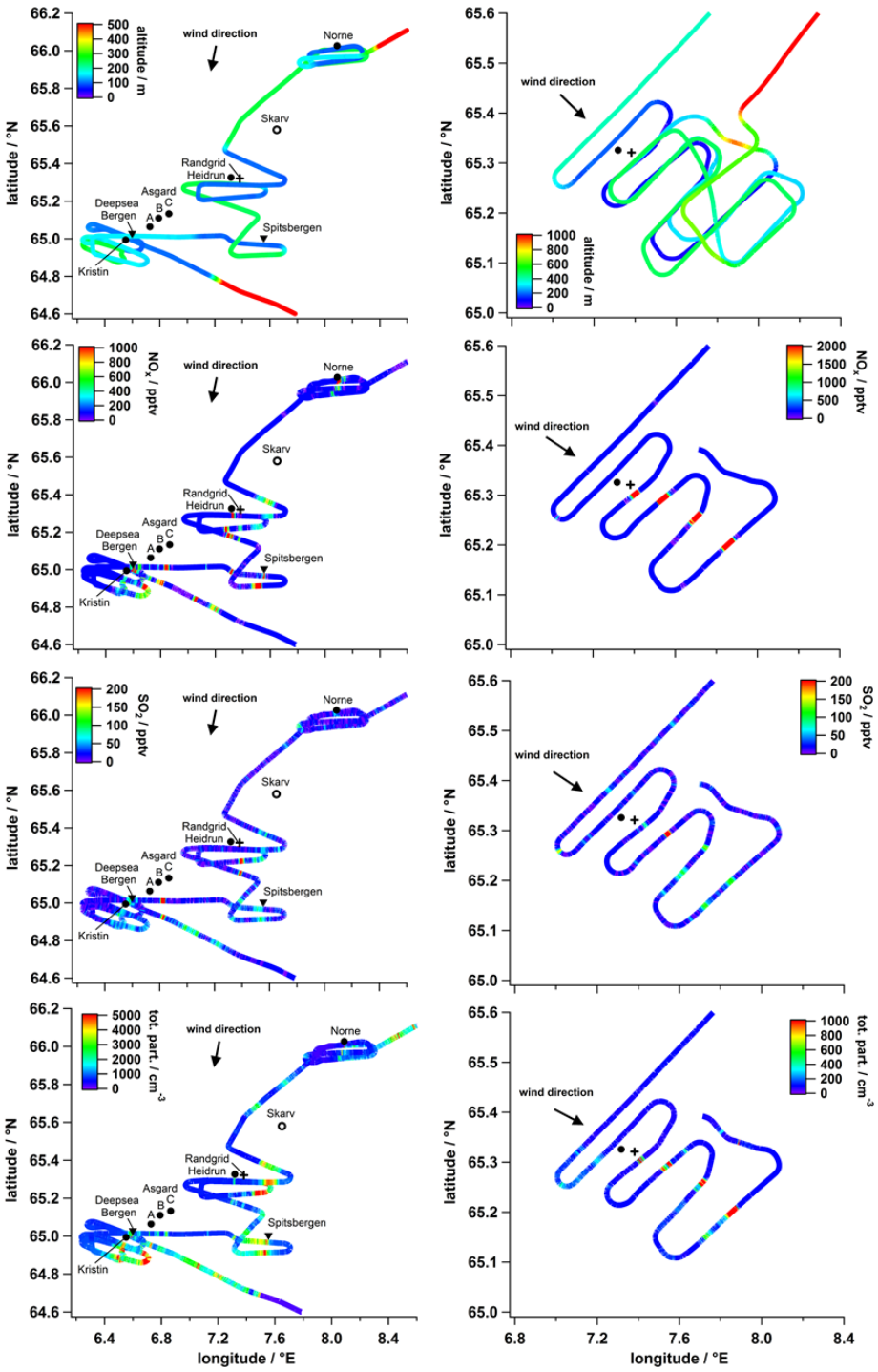

Figure 1. Flight patterns for the missions on 19th (left column) and 20th July (right column). Color code represents flight altitude (a and b) as well as in situ measured NO_x (c and d), SO_2 (e and f), and total number of particles (g and h).

Instrumentation and Flight Description

During the ACCESS campaign, Falcon-20, the research aircraft of Deutsches Zentrum für Luft- und Raumfahrt, was equipped with meteorological, trace gas (NO_x, SO_2, O_3, and CO), and aerosol instrumentations (described in detail in Roiger et al., 2014). Aerosol instrumentations included Condensation Particle Counters (CPC) to measure total, non-volatile and nucleation mode particle number concentrations, Optical Particle Counters (OPC), Ultra-High Sensitivity Aerosol Spectrometer (UHSAS), Passive Cavity Aerosol Spectrometer Probe (PCASP) and Forward Scattering Spectrometer Probe (FSSP) to measure particle size distributions across a wide range of particle sizes, Particle Soot Absorption Photometer (PSAP) to measure absorption coefficient and Single Particle Soot Photometer (SP2) to measure refractory black carbon (rBC) concentrations.

Meteorological conditions were favorable for measurements on 19 and 20 July 2012, allowing for low-level flying in the Norwegian Sea. Wind directions also allowed undisturbed sampling of platform emissions without influence from other pollution sources. The flight on 19 July was aimed at measuring emissions from different types of facilities (oil/gas production platforms, drilling rigs and tankers) listed in Table 1. The flight pattern (Figure 1a) was influenced by local air traffic, including helicopters, and was adapted as needed during the sampling to ensure safe aircraft operation. The flight track on 20 July (Figure 1b) was designed to focus on the Heidrun production platform (with multiple plume crossings at three altitude levels), in order to allow for a more complete characterization of emissions from a single extraction facility and to study plume dilution

Table 1. Annual emissions (derived from measurements combined with modeling within ACCESS and reported) for different hydrocarbon extraction facilities. The reported emissions are from Norwegian Environmental Agency[1]. Note that Randgrid is a mobile transport ship and reported emissions are not available. The Deepsea Bergen and Transocean Spitsbergen are mobile drilling platforms and reported emissions estimates are also not available.

Facility Name	Function	# of analyzed plumes	Derived NO_x	Reported NO_x	Derived SO_2	Reported SO_2	Derived PM	Estimated BC
				tonnes/year				
Åsgard[2]	(all facilities A, B, & C)	-	-	2284	-	239		-
Åsgard B[3]	Gas production platform	1	97	270	-	-	13 – 56	1.3 – 6
Åsgard C	Condensate storage tanker	1	1013	1869	228	239	224 – 929	22 – 93
Deepsea Bergen	Drilling rig	2	240	-	9	-	42 – 172	4 – 17
Transocean Spitsbergen	Drilling rig	1	191	-	7	-	57 – 237	6 – 24
Randgrid	Shuttle tanker	3	173	-	75	-	65 – 270	7 – 27
Heidrun	Oil/gas production platform	3	1234	1775	5	38	5.5 – 23	0.6 – 2.3
Norne	Oil production/storage vessel	3	520	658	4	14	7.6 – 31	0.8 – 3.1

[1]NEA emissions available at: http://www.norskeutslipp.no/en/Offshore-industry/?SectorID=700

[2]Emissions are reported as a total for all three facilities that make up the Åsgard complex. We have divided emissions into the contributions from Åsgard B and Åsgard C using the measurements. Emissions estimates for Åsgard A were not used because Åsgard A was on low production during our measurements. Therefore, from the measurements we only sum emissions from Åsgard B and C.

[3]Measured SO_2 concentrations were close to the instrument detection limit.

and atmospheric transformations. During both missions, elevated concentrations of NO_x, SO_2 and particle emissions were observed downstream of all facilities, as illustrated by the color-code in Figure 1c–g. However, plume sampling and analysis of the Heidrun emissions on 20th July was hampered due to the presence of the Randgrid shuttle tanker (Gross tonnage: 75273) which was anchored near the Heidrun platform, having a different emissions mix than Heidrun (e.g. elevated SO_2 in plumes due to the use of ship fuel).

During the flights, most of the facilities had normal production or drilling activity except Åsgard A, which had low production with only one reinjection compressor running and Norne, which was running under a start-up procedure (Statoil, pers. communication). Heidrun was intermittently flaring according to normal operating conditions (~1% of full flare), and Norne was constantly flaring (due to a shut down earlier in the day) during the measurements. All other facilities were not flaring during the time of our measurements. Flights were conducted in close cooperation with Statoil (Norwegian oil company).

Emissions Estimates

In order to make emissions estimates from operating facilities, we use the Lagrangian model FLEXPART-WRF (Brioude et al., 2013) to model plume dispersion. Briefly, FLEXPART-WRF is run in forward mode using an inert air tracer to simulate the plume dispersion from each point source (facility) studied. We drive the FLEXPART-WRF model with WRF (the Weather Research and Forecasting Model, website: http://www.wrf-model.org, described by Skamarock et al., 2005) run at 2 km × 2 km horizontal model resolution with 40 model levels below 2 km. Emissions exhaust heights were estimated from photos to estimate the platform height and stack height. Emissions in FLEXPART-WRF were injected at the location of the platforms (100 meter horizontal extent and vertically from the surface up to 100 meters above the estimated exhaust height). Measurements are used in conjunction with the plume dispersion forecasts to derive emission rates. In FLEXPART-WRF, an initial emission rate is used for an inert air tracer (1,000 kg/day) and the output is given in tracer mixing ratio. We then use the measured NO_x mixing ratios combined with the FLEXPART-WRF tracer

mixing ratios (extracted along the flight track) to calculate NO_x emissions rates that correspond to the measurements onboard the Falcon-20. To derive absolute emissions estimates, we use the integrated peak area for each plume crossing (example shown in Figure 2, which also shows excellent agreement between measured and modeled plumes in terms of location and extent). The relative amount of other species to NO_x measured in plumes was then used to calculate emissions estimates for these compounds. It is assumed that emissions did not vary significantly during the plume samplings and that NO_x behaves as an inert air tracer and does not undergo chemical conversion to HNO_3 between the point of emission and sampling (between 1-70 km, or ~ 3 - 200 minutes).

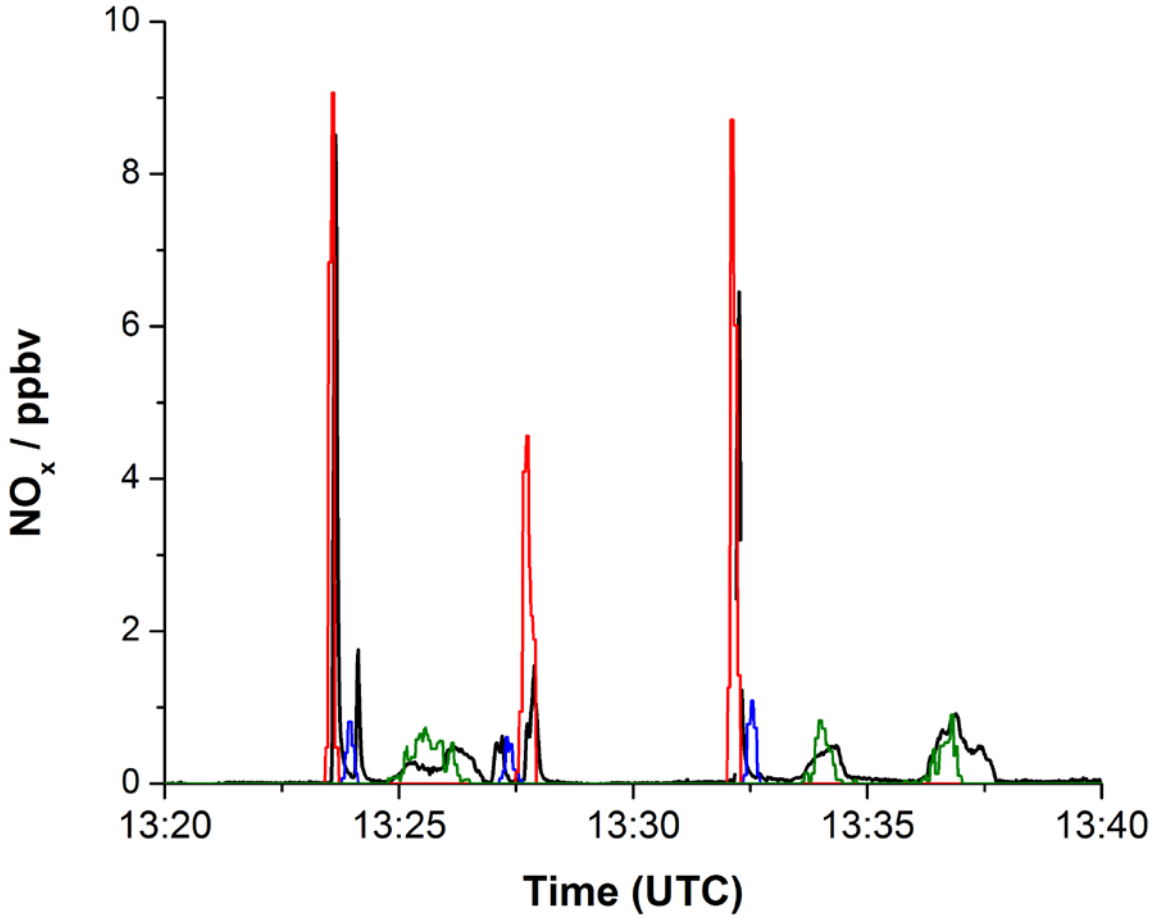

Figure 2. Time-series of NO_x volume mixing ratios for a part of the flight on 19th July. In-situ measured NO_x is given in black and overlaid on NO_x concentrations simulated by FLEXPART-WRF: Heidrun (red), Randgrid (blue) and Skarv (green).

For particulate matter (PM) emissions, volatile and non-volatile particles were treated separately. Volatile particles were assumed to be in the nucleation mode and composed of sulfate and attached water, while non-volatile particles were assumed to be larger and composed of black carbon, organic matter and ash. Different widths of size distribution were used to derive lower and upper emissions estimates. From the assumed size distribution and density, number emission was converted into mass emission. Finally, volatile and non-volatile particle mass emissions were combined to obtain PM emissions.

Although the SP2 was used for measurements of rBC concentrations, it was not used for estimation of BC emissions because the measured size distribution showed that most of the rBC particles were smaller than the SP2 detection limit. A previous study has demonstrated the limitation of using SP2 for rBC measurements in fresh plumes (Buffaloe et al. 2014). PSAP is another instrument that is frequently used in BC measurements (Buffaloe et al., 2014; Petzold et al., 2008) but because of short residence time in plumes, not enough BC was accumulated on filters to make accurate measurements. Therefore, BC emission was estimated by assuming 10% of the non-volatile particle mass to be from BC (Petzold et al., 2010). SP2 measurements most likely underestimated rBC concentrations but they still showed positive correlation with non-volatile particle concentrations.

The estimated annual emissions for NO_x, SO_2, PM and BC are presented in Table 1. Åsgard A, which had low production and Skarv, which was under installation, are not included in the emissions estimates. Kristin was also not included in the analysis because its plume was mixed with plumes from other facilities (see Figure 1 a). NO_x and SO_x emissions reported to the Norwegian Environment Agency are also shown. Reported emissions of PM and BC, and data for Randgrid were not available. Reported emissions are usually calculated from $E_{p,s} = A \times EF_{p,s} \times (1–ER/100)$ where A is the activity rate, $EF_{p,s}$ is the emission factor (amount of pollutant per weight, volume, distance or duration) specific to pollutant (p) and source category (s) and ER is the overall emission reduction efficiency.

Derived NO_x emissions are slightly lower than the reported NO_x emissions. For SO_2, estimated emissions are also close to the reported emissions. The main facility that

emits SO_2 from the Åsgard complex is Åsgard C. While we were not able to estimate the SO_2 emissions from either Åsgard A or B, the total estimated for Åsgard C is in good agreement with the total reported for all installations. Sources of SO_2 include combustion of diesel and natural gas in engines and turbines, which contain sulfur impurities. SO_2 is formed from oxidation of sulfur contained in the fuel, and its emission is entirely dependent on the sulfur content of the consumed fuel, and not affected by combustion technology such as engine size. Diesel generally has higher sulfur content than natural gas, and consequently its combustion leads to higher SO_2 emission. Estimated PM and BC emissions varied greatly depending about the assumptions made about the particle size distribution. Most of the PM mass was derived from non-volatile particles, for which larger size and density were assumed than for volatile particles.

The number of analyzed plumes was different for each facility as shown in Table 1. Only one plume was used to derive emissions for Åsgard B, Åsgard C, and the Transocean Spitsbergen, therefore emissions estimates for these facilities are more uncertain than those for Deepsea Bergen, Randgrid, Heidrun and Norne (where multiple plume crossings were possible). In particular, Heidrun and Randgrid plumes were sampled on two different days. The magnitude of emissions showed some variability, perhaps due to different operating conditions, but emission characteristics (*e.g.* larger SO_2 emissions for Randgrid) are consistent.

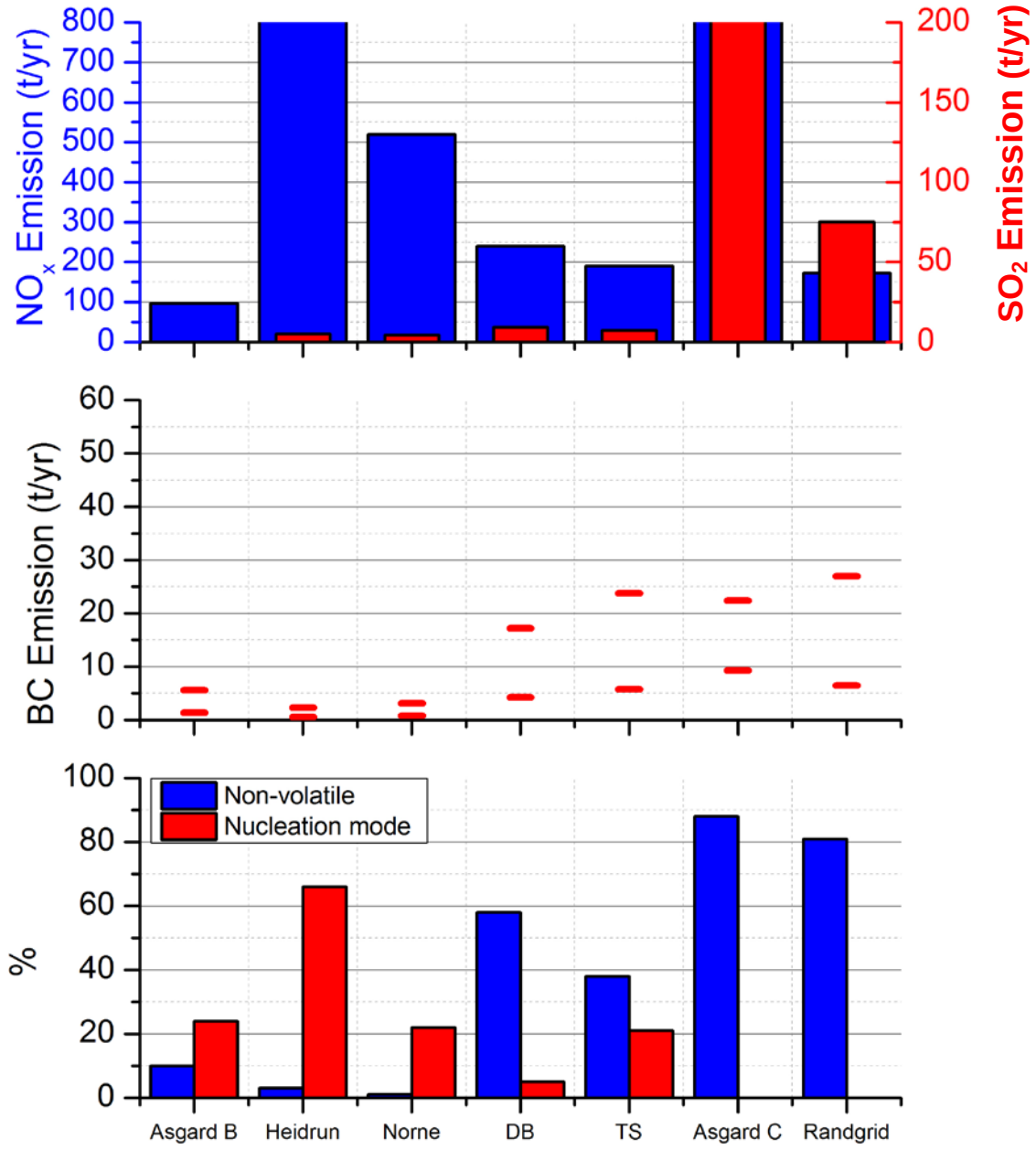

Figure 3. Estimated annual (a) NO_x (blue), SO_2 (red) and (b) black carbon emissions for sampled production facilities (Asgard B, Heidrun, Norne), drilling rigs (Deepsea Bergen, Transocean Spitsbergen), and tankers (Asgard C, Randgrid). For black carbon, lower and upper estimates are shown. (c) Non-volatile and nucleation mode particle fractions measured in the plumes.

Emission Characteristics

Distinct differences in emission characteristics for different types of facilities were observed, and are presented in Figure 3. The observed differences between tankers, drilling rigs and production facilities can be attributed to different combustion technology and fuel consumption. The biggest difference is due to the different emission characteristics of natural gas and diesel combustion; combustion of natural gas is known to result in significantly lower emissions of NO_x, SO_2 and PM (EIA). Figure 3 shows that storage and shuttle tankers (Åsgard C and Randgrid), which operate on diesel, are characterized by high SO_2 emissions, high non-volatile particle fractions (~80%) and accordingly, high BC emissions. Nucleation mode particles were not observed, which suggests that all particles were > 14 nm, and the aerosol size distribution measured by UHSAS showed enhanced concentration above background for particles < 100 – 150 nm. Drilling rigs (Deepsea Bergen and Transocean Spitsbergen) were also high BC emitters.

In contrast, production facilities (Åsgard B, Heidrun and Norne) emitted particles, which were mostly volatile (non-volatile particle fraction < 10%), and they had low SO_2 emissions. Unlike tankers and drilling rigs, the UHSAS size distribution for these facilities did not show enhancements above background and therefore, the particles are expected to be < 60 nm (lower detection limit of UHSAS). Actually, they exhibited high nucleation mode particle fractions (up to 66%), which suggest new particle formation. Species with low vapor pressure such as H_2SO_4 and volatile organic carbons (VOCs) are typical aerosol precursors (Alam et al., 2003; Kulmala et al., 2004). Since the measured SO_2 concentrations were low for these facilities, the nucleation mode particles are unlikely to be sulfate aerosols, which have been observed in exhausts of aircraft engines (e.g. Schröder et al. 1998; Brock et al., 2000) and e.g. a coal-fired power plant (Stevens et al. 2012). Thus they are more likely to be secondary organic aerosols formed from VOCs emitted from venting or leakage. Large amounts of VOC emissions from (on-shore, land based) production facilities in the United States have been previously observed (Pétron et al., 2014 and references therein). However, this hypothesis needs to be confirmed by future studies which include VOC measurements

BC emissions for production facilities were low; even Norne which was continuously flaring during the measurements showed negligible BC emissions, and actually had the

lowest non-volatile particle fraction (1%). This result seems to contradict Stohl et al. (2013) who predicted (Russian) flaring emissions contribute significantly to Arctic BC surface concentrations. In addition, the low SO_2 concentrations in the Norne plume suggest that the flared gas was low in sulfur.

Modeling the influence of emissions on Atmospheric Composition

A chemical transport model has been used to study the impacts of emissions from oil/gas facilities in the Norwegian Sea on atmospheric composition. For our studies, we use the regional chemical transport model, WRF-Chem (the Weather Research and Forecasting (WRF) model with Chemistry, described in Grell et al., 2005). The model simulates the emission, transport, mixing, and chemical transformation of trace gases and aerosols simultaneously with the meteorology. The model can be used for investigation of regional-scale air quality, measurement analysis, budget studies, and interactions between clouds and chemistry. In our study, we use the model for interpretation of field measurements, to study the influence of offshore platform emissions on the concentrations of gases and aerosols (air quality), and to study the fate of pollution emitted from hydrocarbon extraction platforms to the air. As it was already noted, one of the largest uncertainties in the modeling of the Arctic pollution is the contribution of emissions from oil/gas extraction facilities. Current anthropogenic emissions inventories different significantly in how they include oil/gas extraction emissions. This report provides a description of the some results about the study of the effects of emissions from oil/gas extraction facilities on pollution level in the Arctic, after a better characterization of the emissions. The study is conducted in the frame of the ACCESS project. The work also focuses on the Norwegian Sea region during ACCESS aircraft campaign of summer 2012.

Emissions used in Chemical Transport Modeling (CTM)

In this section we compare the emissions from oil/gas extraction activity in the Norwegian Sea estimated by MACC-TNO inventory and the official Norwegian emissions (http://www.norskeutslipp.no/en/Offshore-industry/?SectorID=700). MACC-TNO is a

gridded high resolution European inventory (7 x 7 km) of anthropogenic emissions, and provides for each EMEP SNAP sector the total annual emissions of NO_x, SO_2, NMVOCs (non methane volatile organic compounds), CH_4, NH_3, CO, PM_{10} and $PM_{2.5}$ (Kuenen et al., 2014). The emissions on Norwegian Sea region are reported as point sources in Table 2. The MACC-TNO inventory takes into account the emissions of NO_x and NMVOC from the different facilities, but it does not include the emissions of SO_2, PM, BC and OC.

In order to understand how well the MACC-TNO inventory is representative of the platform emissions in Norwegian Sea, we compared the inventory to the NEA emissions, shown in Table 2. NO_x emissions estimated by MACC-TNO are less than a factor 10-100 with respect to official emissions, whereas NMVOCs emissions are higher than official values of about a factor 2. Moreover, Norwegian data takes also into account the SO_2 emissions. Both data set give the total Asgard emissions, i.e. the emissions are not divided for the different facilities. We split the total values of NO_x, NMVOCs and SO_2 emissions for the three facilities (Asgard A, B, and C) by using the areas below the curves reported in Figure 4. The areas are proportional to the emissions of a given compound because the measurements are sampled downwind facilities. The total NO_x is estimated to be emitted for the 6%, 12%, and 82% by Asgard A, B, and C, respectively. SO_2 is all assigned to Asgard C. Concernig the splitting of NMVOC, we used the area below the curves of nucleation mode particles. Therefore we attribute the 30%, 47% and 23% of total NMVOC to Asgard A, B, and C, respectively. Norwegian data (as well as MACC-TNO emissions) do not include the aerosol emissions. The emissions of PM, BC and primary OC are estimated by using the emission factors of 2004 reported by Peters et al. (2011) for Norway. Emitted aerosol mass is calculated by assuming that is proportional to NO_x emissions through the ratio between emission factors of a given aerosol compound and NO_x. The values obtained are reported in Table 2.

Table 2. Total annual emissions from facilities on Norwegian Sea reported by MACC-TNO inventory and estimated from Norwegian Environment Agency (NEA). The units are in tonnes per year.

	NO_x		NMVOC		SO_2		PM		EC		OC	
	TNO	NEA	TNO	NEA	TNO	NEA	TNO	NEA	TNO	NEA	TNO	NEA
Kristin	-	180	57	23	-	4	-	4	-	1	-	1
Asgard (total)	63	2284	8780	5739	-	239	-	115	-	14	-	15
Asgard A	-	145	-	1747	-	-	-	3	-	1	-	1
Asgard B	-	270	-	2675	-	-	-	6	-	2	-	2
Asgard C	-	1869	-	1317	-	239	-	106	-	11	-	12
Heidrun	61	1775	550	255	-	8	-	38	-	10	-	12
Norne	33	658	560	325	-	5	-	14	-	4	-	4

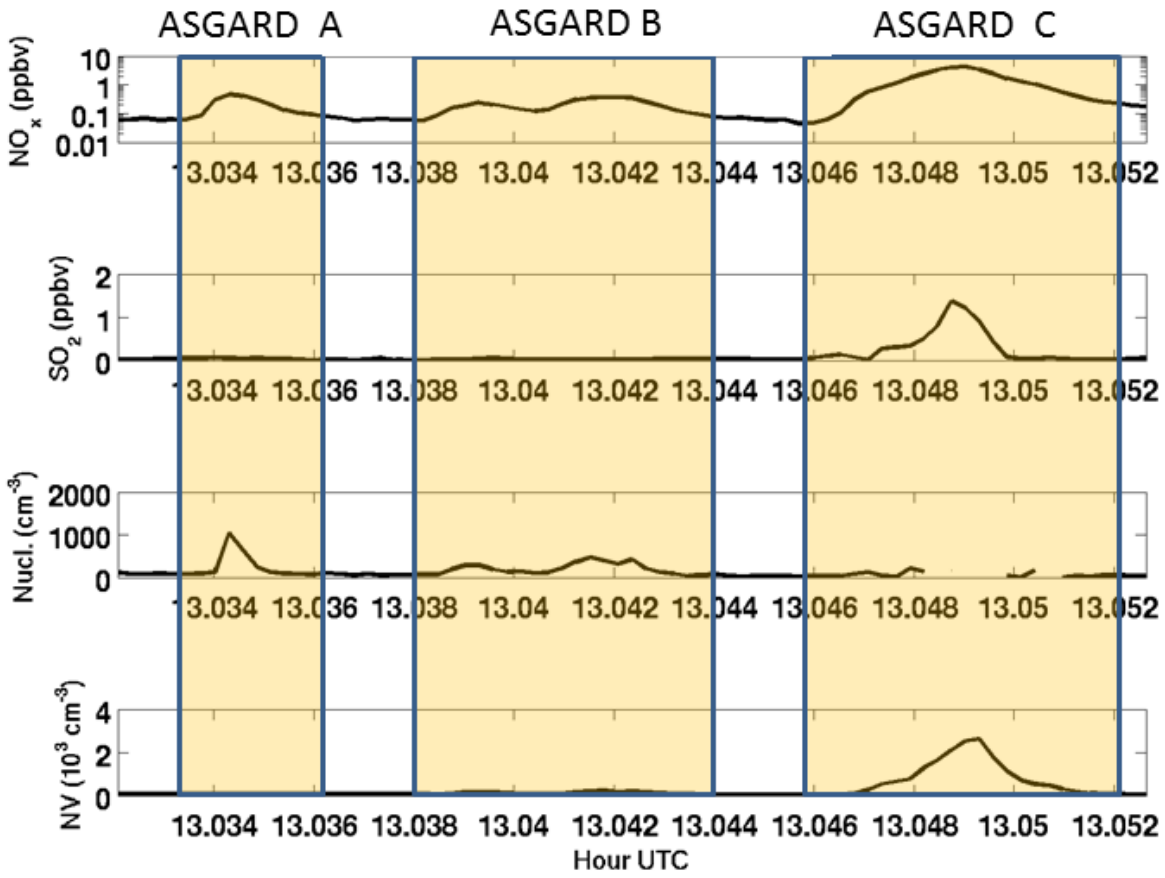

Figure 4. Time series of NO_x and SO_2 mixing ratio, nucleation mode and total non-volatile particle number concentration measured in the plumes of Asgard facilities during the flight of 19 July.

Regional model description and setup

The model used to study the evolution of the plumes released from oil/gas facilities is the version 3.4.1 of Weather Research and Forecasting model with Chemistry (WRF/Chem) (Grell et al., 2005), a regional CTM. The gas-phase/aerosol mechanism used is the RACM/MADE/SOA-VBS option. The model is configured with two 1-way nested domains at 10 and 2 km resolution centered on the Norwegian Sea. The meteorology of domain 1 is initialized with 6-hourly high resolution (0.125° x 0.125°) ECMWF analysis. The outputs of Model for OZone and Related chemical Tracers (MOZART) (boundary conditions from Emmons et al., 2010, as described in Pfister et al., 2011) are used as chemical boundary conditions for domain 1. Meteorological initial and boundary conditions of domain 2 are taken from simulations of domain 1. The same is

done for chemical boundary conditions of domain 2. The chemical state is restarted from previous simulation for both domains.

Regional model results

In this section we discuss the modeling results obtained in the high resolution by using Norwegian emissions. Figure 5 shows the comparison between observed and modeled O_3 and NO_x along the flight track. The analysis of O_3 reveals that the modeled background ozone (far from plumes) is overestimated. The bias is in average of 1.3 ppbv (+5%) for 19 and 1.5 ppbv (+6%) for 20 July. WRF/Chem reproduces the observed values of NO_x for Asgard C and Heidrun installation, but underestimates the mixing ratio of Norne plumes. Sometimes the model tends to shift the observed plumes because of small errors in simulating wind speed and direction. The model also captures the decrease of the ozone with respect to background within plumes. NO_x and O_3 in plumes are reproduced with a correlation of 0.70 and 0.45, respectively. The bias found in predicted O_3 is sensitive to differences in the relative amounts of NO_x and NMVOC emissions, i.e. depend on the flaring activities of the facilities. The influence of variations in NO_x and NMVOC emissions on O_3 has been investigated through sensitivity runs. WRF/Chem shows that close to the platforms (10-30 km downwind) the O_3 is sensitive to NO_x emissions, but not to NMVOC emissions. Finally, simulation results show that oil/gas emissions increase the regional background of black carbon at surface by +48% (+2.2 ng/m^3). $PM_{2.5}$ enhancements are +7.8 ng/m^3 (+11%), while the average contribution to sulfate is +3.9 ng/m^3 (+2%). Surface change of secondary organic aerosol is estimated to be +12%.

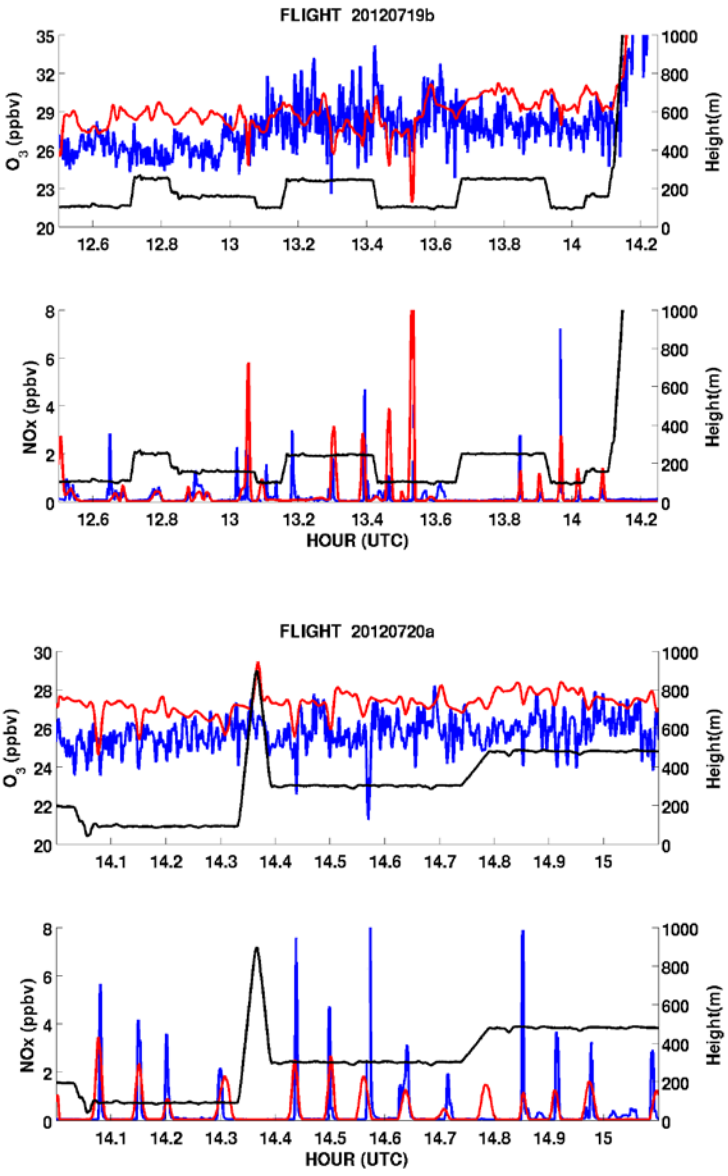

Figure 5. Time series of observed (blue) and modeled (red) NO_x and O_3 mixing ratio along the flight track on 19 (top) and 20 (bottom) July.

Conclusions

NO_x emissions derived from measurements and modeling within ACCESS were smaller than reported values for most facilities, whereas SO_2 emissions showed better agreement. PM and BC emissions estimates varied over an order of magnitude, depending on the assumptions made about particle size distribution. Detailed measurement of particle size distribution are needed in future studies in order to obtain more accurate PM and BC emissions. Distinct emission characteristics were observed for different types of facilities. Tankers and drilling rigs emitted high levels of SO_2, BC and PM due to large amount of combustion in diesel engines. In contrast, production facilities, which operate mainly on natural gas, emitted low levels of SO_2 and BC. Plumes for these facilities contained high fraction of volatile, nucleation mode particles, which is probably the consequence of new particle formation from VOC emissions. Future studies should include VOC measurements to confirm this hypothesis, and also to investigate their role in ozone formation. The measured BC emission from gas flaring was low for the facilities sampled here but this will vary depending on the composition of the flared gas and the degree of smoking. Analysis of night-light satellite data may be useful for this purpose.

The results of the current study are limited to measurements over two days, and to facilities in the Norwegian Sea. Further in-situ measurements at broader spatial and temporal scales are needed to determine the representativeness of the emissions estimates derived from this study. Existing bottom-up emissions inventories should be evaluated through more measurements for a more accurate prediction of future Arctic air pollution and associated cliamte impacts. Also, emissions from permanent facilities have been reduced in recent years whereas emissions from mobile rigs have increased. This is due to increased activity involving mobile facilities, which is the result of several new developments taking place (FACTS 2014). As the melting of Arctic sea-ice presents opportunities for new development, use of mobile drilling rigs will increase further. Also, Peters et al. (2011) predicted rapid emissions growth from oil and gas transport via ship as the location of hydrocarbon production moves into locations requiring more ship transport relative to pipeline transport (Peters et al., 2011). Since shuttle tankers

and drilling rigs were found to be high BC emitters, BC emission due to hydrocarbon activities are expected to increase, which, in turn, will increase future BC surface concentration in the Arctic. Shuttle tankers will also have a significant impact on atmospheric SO_2 concentrations.

In addition, we have investigated oil/gas extraction in the Norwegian sea using regional chemical transport modeling combined with measurements taken as part of the ACCESS aircraft campaign (July 2012). We use high resolution numerical simulations performed with the WRF-Chem model with source emissions that represent individual operating platforms. Specifically, emissions of oil/gas facilities in Norwegian Sea are taken from TNO-MACC inventory and from emissions reported by Norwegian Environment Agency (NEA). Large differences have been found between the two inventories. NO_x emissions in TNO-MACC are much smaller compared to Norwegian emissions by a factor 20-30, whereas the TNO-MACC NMVOC emissions are larger than NEA data by a factor 1.5-2. Because these inventories do not report PM primary emissions, aerosol emissions were estimated using emission factors reported for the Norwegian Arctic. Model evaluation shows that with TNO emissions WRF-Chem does not reproduce the observations of NO_x, O_3, and aerosol particles close to the facilities. NEA emissions are combined with estimated aerosol emissions based on the measurements for the base run (CRTL run), which most accurately represents air pollution measured onboard the Falcon-20 during flights focused on studying oil/gas emissions. The influence of variations in NO_x and gas phase organic (NMVOCs) emissions on predicted pollution concentrations was investigated through sensitivity runs.

Within the ACCESS project, emissions hydrocarbon extraction and exploration/drilling platforms were studied and put into the context of reported emissions (Norwegian Environment Agency) and emission used by the European air quality modeling community. The impact of these emissions to air have been studied using regional chemical transport modeling, which shows that both ozone and aerosol concentrations (main components that make up air pollution) are sensitive to emissions from extraction platforms.

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