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Contents

1. Introduction

This report provides an assessment of gridded emission datasets related to oil and gas extraction activities in the Arctic region. Figure 1 shows the production and reserves of natural gas and oil for countries in the Arctic region and the North Sea. Currently, Russia has the monopoly in terms of production and reserves for natural gas. For oil, Russia and the United States are the main producers but Canada has most of the oil reserves. The North Sea is also an important production region primarily for oil.

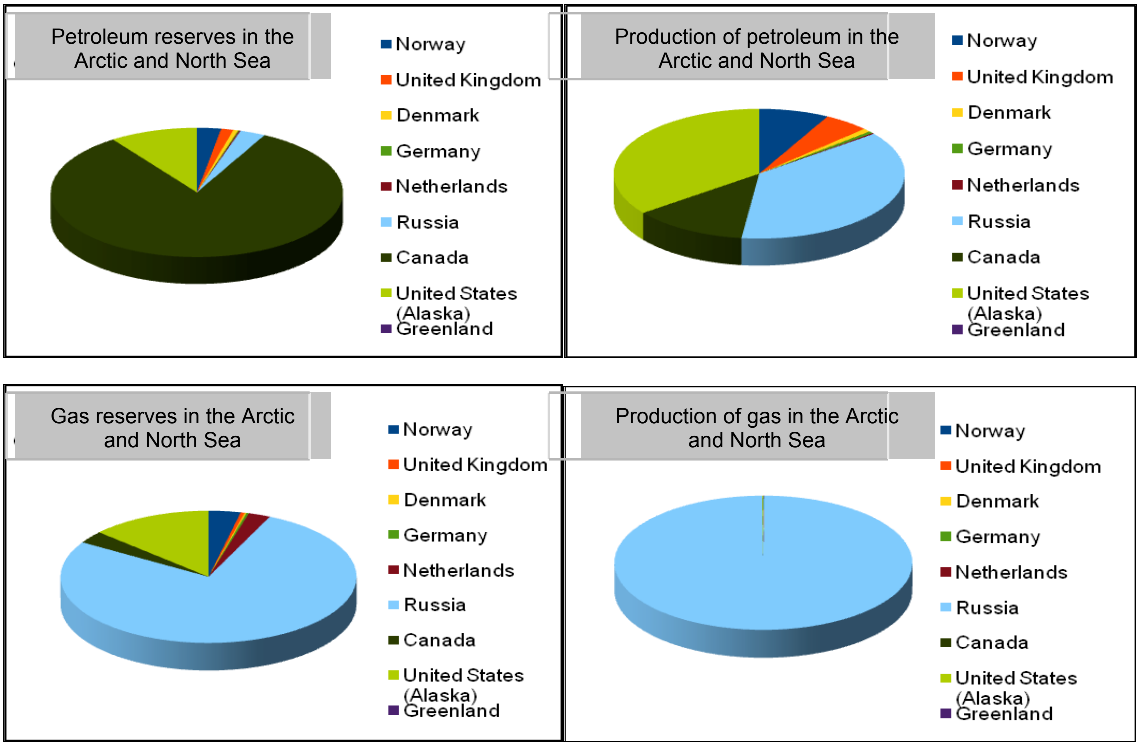

***Figure 1** – Production and reserves of gas and oil in the Arctic and North Sea (CIA World Fact book)*

This report is laid out as follows. In section 2, we provide an assessment of several currently available emission datasets. There is a focus on the Norwegian Sea region due to the fact that this is where the ACCESS aircraft campaign was planned and took place in summer 2012. It should also be noted that, due to flight restrictions, it was not possible to make flights over Russian air space. In section 3, we summarize available emission estimates for several oil and gas facilities in the Norwegian Sea. The aircraft campaign, which made dedicated flights around platforms, and preliminary data from the campaign are described in section 4 together with the planned methodology for determining independent emission estimates from the aircraft data. In section 5, we highlight current knowledge of oil/gas flaring emissions, which have recently been recognized as potentially very important source of pollution in the Arctic.

2. Current emissions inventories

In this section, we describe the current state of knowedge about emissions related to oil/gas extraction in/near the Arctic off the coast of Norway. This region is the focus due to overlap with the ACCESS aircraft campaign (described below in Section 4) in July 2012. Figure 2 shows nightlights (illuminated areas of the Earth's surface at night detected via satellite) from the DMSP Defence Meteorological Satellite Program). This shows (in green) regions where nighlights were detected that are associated with oil/gas extraction activities in the North and Norwegian Seas. We note the location of the Heidrun facility, which was one focus of the ACCESS aircraft campaign (in summer 2012).

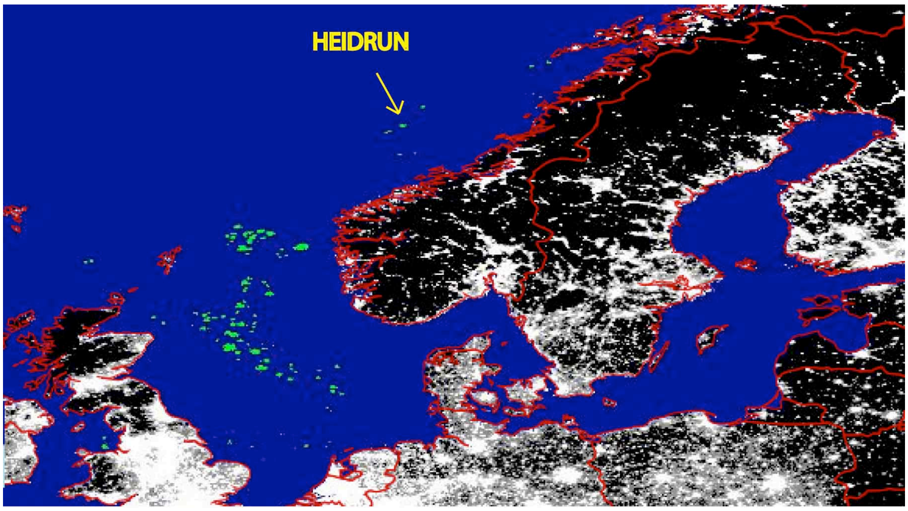

Figure 2 – *Night-lights over the North Sea and Norwegian Sea in 2003 (http://mapserver.ngdc.noaa.gov/cgi-bin/public/ms/poster/viewer)*

Some flaring and/or venting is a necessary practice in the production of oil and gas and results in release of methane, CO_2, and air pollutants. Flaring is the controlled burning of gas in the course of oil and gas production operations. Gas that is flared may be excess to the commercial demand, unburned process gas from the processing facility, vapours collected in tanks as they are filled, or excess gas during equipment equipment changegovers and maintenance. Flaring also occurs during a production shutdown which can require flaring off all the gas stored at the facility to prevent a catastrophc situation from occuring (Kearns et al., 2000). Venting is the controlled release of gases into the atmosphere, which can occur duing oil and gas production operations. In the case of venting, gases associated with the oil production are released directly to the atmosphere and are not burned (Kearns et al., 2000). These and other procedures (transport, generating power, etc.) related to oil and gas extraction lead to emissions of different species (gaseous and aerosols) which have an impact on atmospheric composition. These include methane, non-methane volatile organic compounds (NMVOCs), carbon monoxide and nitrogen oxides which can lead to production of ozone in the troposphere. They also include aerosol precursors such as sulphur dioxide which can form sulphate aerosols, and black carbon (BC) aerosols. Emissions of other aerosols are grouped into emissions of particulate matter (PM). Both ozone and aerosols impact the climate by either warming or cooling the atmosphere and inceasing the concentrations of species that determine air quality.

For this report, emissions from 4 gridded datasets (inventories) were examined:

- EDGAR 4.2 (Emissions Database for Global Atmospheric Research): estimates from the European Joint Research Centre (Italy) calculated using emission factors (ratio of tonnes of compound emitted to tonnes of compound released into the atmosphere due to venting or flaring activities based on technologies used between 1970-2008. Emissions are available on a 0.1x0.1 degree grid.
- Peters et al. (2011): Recent study using emission factors and activity for 2004. Future emissions are also estimated for 2030 and 2050. Emissions are estimated for the Arctic in the region inside the thick black/yellow lines in Figures 6a and b respectively. The 2004 emissions are distributed on a 1×1 grid using field-by-field data on historic oil and gas production, estimated resources, and additional data such as stage of production, and on/off-shore. The emission factors per unit oil and gas extracted come from a variety of different data sources. Default values are from a global dataset based on voluntary reporting by oil and gas companies, but most of these default values were updated using national statistics. Most national estimates are obtained by dividing the total oil and gas emissions by the net oil and gas extracted in each region. Regionally averaged emission factors is used, corresponding five regions, instead of attempting to estimate site specific (gridded) emission factors which may vary widely for different fields.
- TNO-MACC (Monitoring Atmospheric Composition and Climate): The TNO gridded emission inventory is a detailed European-wide, high-resolution (1/8° x 1/16° lon-lat) emission inventory for NO_x, SO_2, NMVOC, CH_4, NH_3, CO, PM_{10} and $PM_{2.5}$ for the year 2005. The database used, as much as possible, official reported emission data per source sector. Consistency checks have been performed on the data and where necessary alternative emission data have been used from the IIASA RAINS model or TNO expert knowledge. Emissions have been split in point sources and area sources and are available in aggregated source categories (SNAP level 1). The total emissions per source category by country were subsequently spatially distributed using different proxy parameters and/or proxy maps. Further details can be found in Denier van der Gon et al. (2010).
- IIASA (International Institute for Applied Systems Analysis): Emissions provided as part of a collaboration with the FP7 EU ECLIPSE (Evaluating the CLimate and Air Quality ImPacts of Short-livEd Pollutants) project. Within ECLIPSE, IIASA has calculated a separate gas flaring emission layer drawing on the activity (flared volumes) and spatial distribution developed by Global Gas Flaring Reduction (GGFR) initiative of the World Bank. All pollutants are distributed according to this spatial pattern except for CH_4, which is distributed over land only in the current version. Emission factors are an average of the limited number of measurements (mostly done on industrial or lab scale flares rather than real filed operations). Emissions of several pollutants were spatially distributed by 0.5x0.5 degree grid.

The characteristics and the website for each dataset are given in Table 1 overleaf.

Table 1 *– Emissions datasets examined in this report*

Dataset	Chemical compounds	Spatial resolution (degs.)	Year	Website
EDGAR 4.2	CH_4, NO_x,$NMVOC_s$, SO_2, PM	0.1x0.1	2008	edgar.jrc.ec.europa.eu
Peters et al. 2011	BC, CH_4, CO_2, CO, $NMVOC_s$, NO_x, PM, SO_2	1.0x1.0	2004	www.atmos-chem-phys.net/11/5305/2011/
TNO-MACC	CH_4	0.5x0.5	2003 to 2007	www.gmes-atmosphere.eu
IIASA-ECLIPSE	BC, OC, CO, NO_x, SO_2, NMVOC, PM) and CH_4	0.5x0.5	2005 to 2010	gains.iiasa.ac.at ; eclipse.nilu.no

In this section, we compare emission datasets for particular compounds over the Norwegian Sea region. Figure 3 shows a comparison between SO_2 emissions from EDGAR 4.2, Peters et al. (2011) (hereafter called Peters) and TNO-MACC related to oil extraction. Only the emissions from Peters and IIASA ECLIPSE (not shown) have emissions for the facilities located in the Norwegian Sea, including the Heidrun area. The other datasets have no emissions of SO_2 over oceans linked to oil extraction.

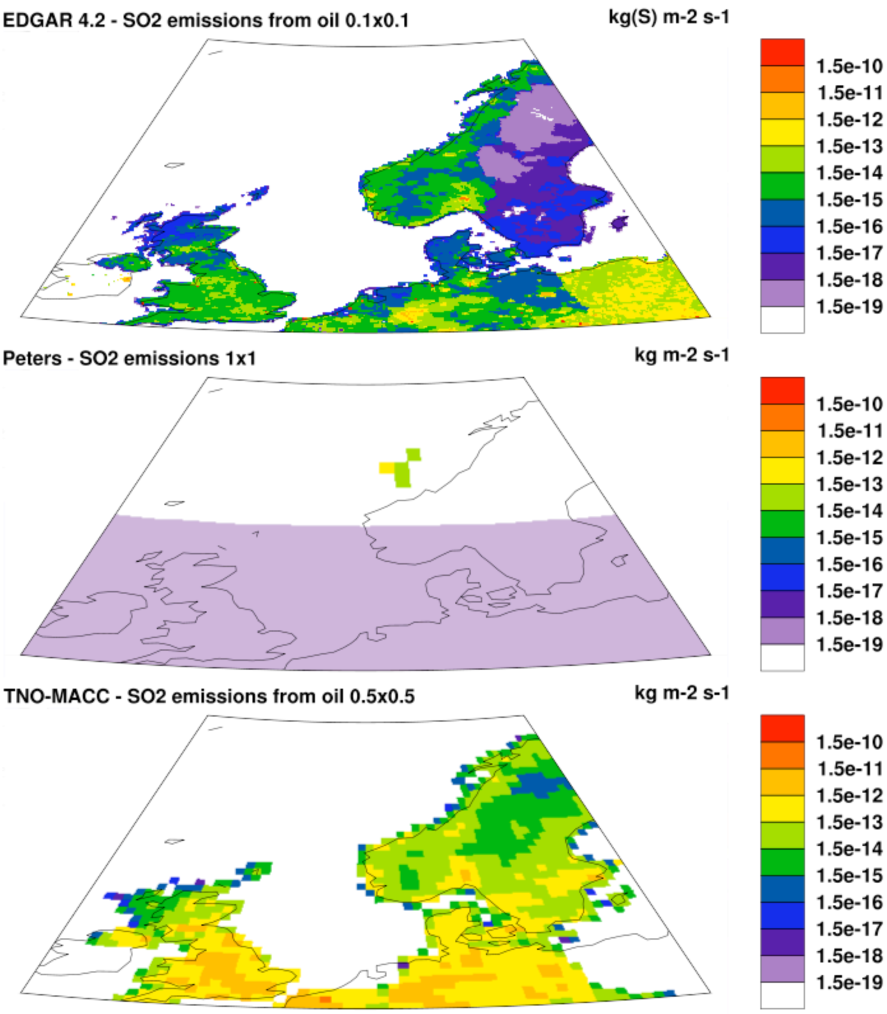

Figure 3 *– SO_2 emissions from oil extraction from EDGAR 4.2 inventory (http://edgar.jrc.ec.europa.eu/overview.php?v=42), from oil/gas extraction given by Peters et al. (2011), and emissions from oil from the TNO-MACC emissions inventory (Denier van de Gon et al., 2010, provided online at ftp://neptunus.tno.nl/TNO/MEP/EM/MACC/).*

Figure 4 shows a comparison of CH_4 emissions from EDGAR 4.2, Peters and TNO-MACC related to oil/gas extraction. It is clear the EDGAR 4.2 emissions for this category also contain emissions from shipping, a point confirmed to us by the group who developed these emissions. It is therefore, not possible, at this stage, to use this emission inventory to study impacts of oil/gas extraction specifically within ACCESS. In addition, only the emissions from Peters show emissions for extraction activities related to the Heidrun region for CH_4. The ECLIPSE emissions do include venting but these are not attributed to off-shore production in the current version. These emissions are significant and of the same order of magnitude as those over continental regions (linked to leaks from refineries, petrol stations etc.).

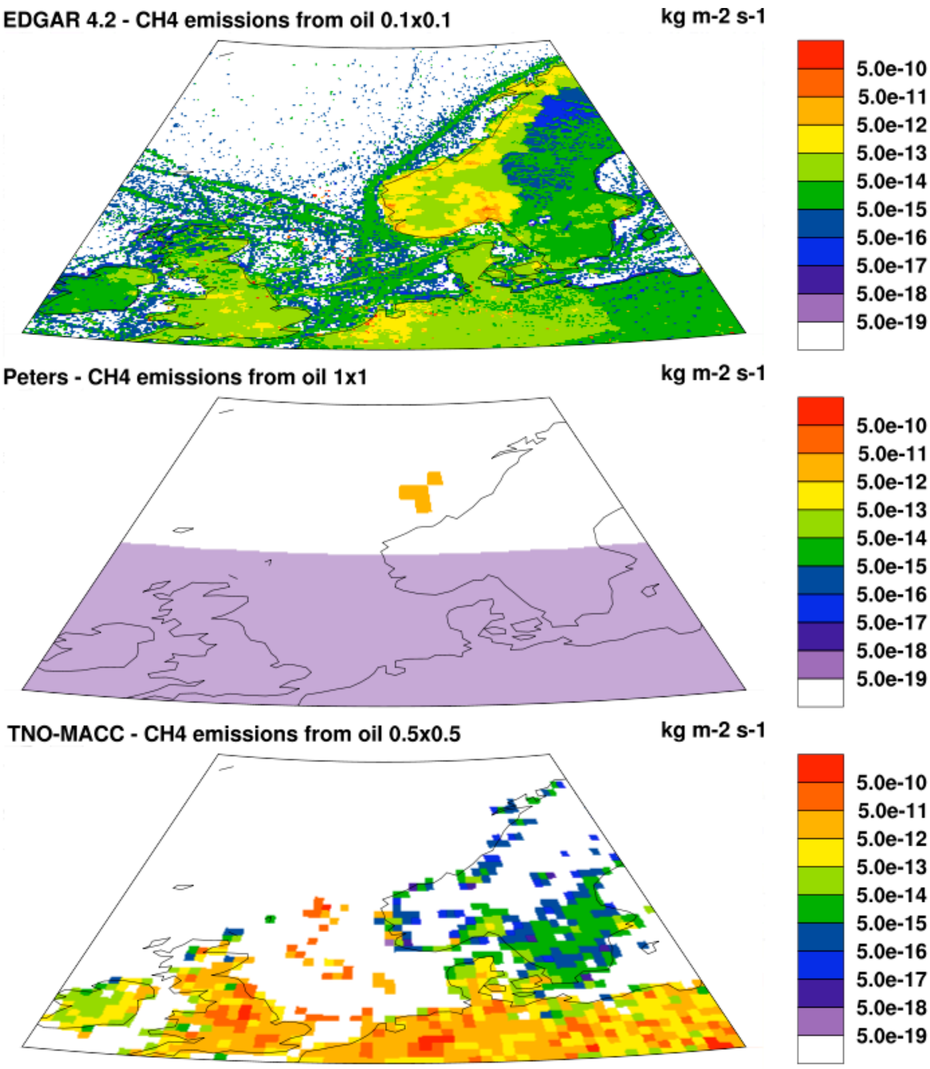

***Figure 4** – Methane emissions oil according to the EDGAR 4.2 emissions inventory, emissions from oil/gas extraction given by Peters, and from the TNO-MACC emissions inventory (Denier van de Gon et al., 2010, ftp://neptunus.tno.nl/TNO/MEP/EM/MACC/).*

Figure 5 shows a comparison of NMVOC emissions from TNO-MACC, Peters, and IIASA related to oil extraction. We have not included EDGAR 4.2 here since it is clear from the analysis presented previously that these emissions cannot be used in their current form. Emissions from TNO-MACC also show emissions from oil and gas platforms in the North Sea only. They are higher than those estimated by IIASA which are also more spread out. The TNO-MACC emissions also appear to include some sort of background emissions, possibly from shipping. Both the emission inventories from IIASA and Peters show emissions for the Heidrun field but emissions are smaller in the IIASA dataset. This point is revisited in the next section where we examine emissions for specific facilities within the Heidrun field.

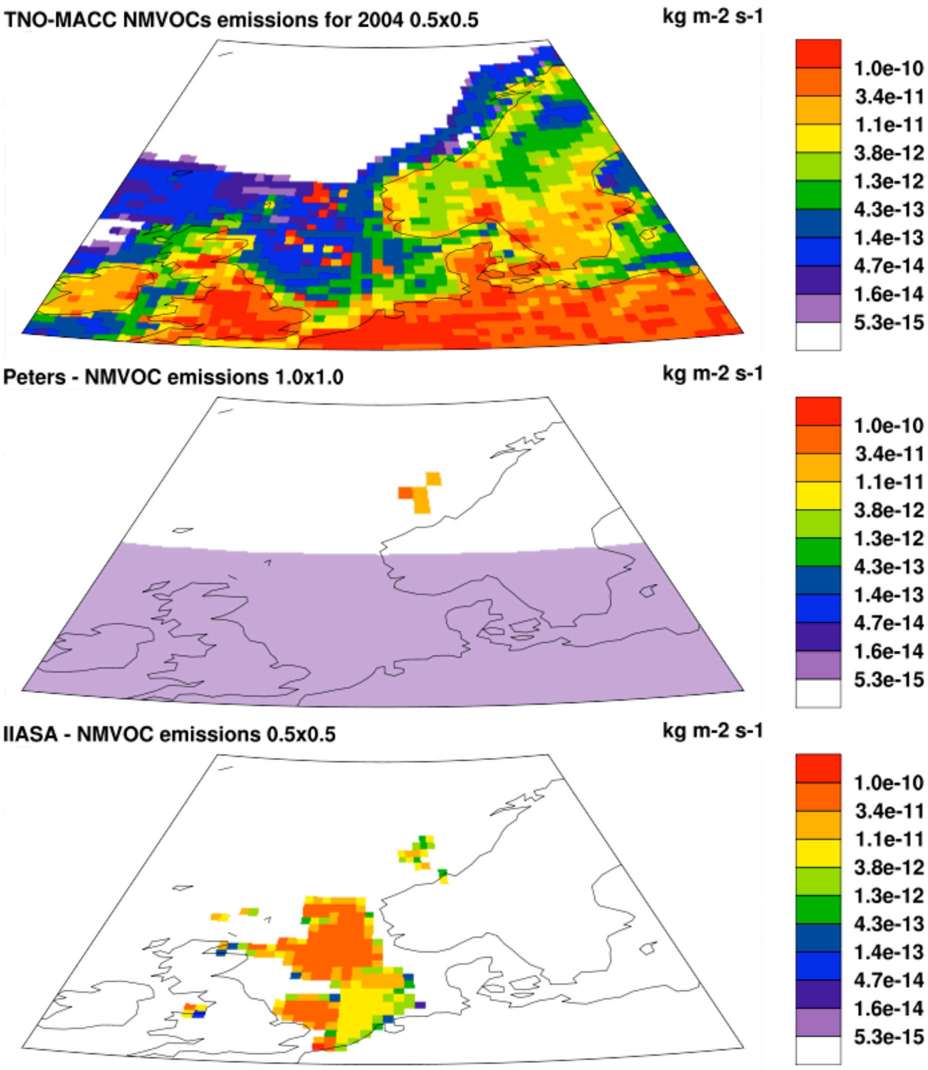

***Figure 5** – Non-methane volatile organic hydrocarbon emissions from oil given by TNO-MACC emissions inventory (Denier van de Gon et al., 2010, provided online at ftp://neptunus.tno.nl/TNO/MEP/EM/MACC/), emissions from oil/gas extraction given by Peters, and emissions provided by IIASA (International Institute for Applied Systems Analysis) for use in the ECLIPSE project.*

The above analysis shows that there little or no consistency between emission inventories for venting and flaring emissions from oil/gas extraction over the North Sea and Norwegian Sea with certain inventories including shipping emissions in this category. The most recent studies are from Peters et al. (2011) focusing on emissions at high northern latitudes and IIASA ECLIPSE global emissions (e.g. see Stohl et al., 2013). Differences are found between these datasets over the Norwegian Sea.

In Figure 6 we show Arctic wide oil and gas production totals region from Peters and NMVOC emissions from IIASA ECLIPSE (present day, Figure 6a) and production estimates for 2030 from Peters (Figure 6b). It can be seen that there is already significant activity in Alaska and also, in particular over Russia.

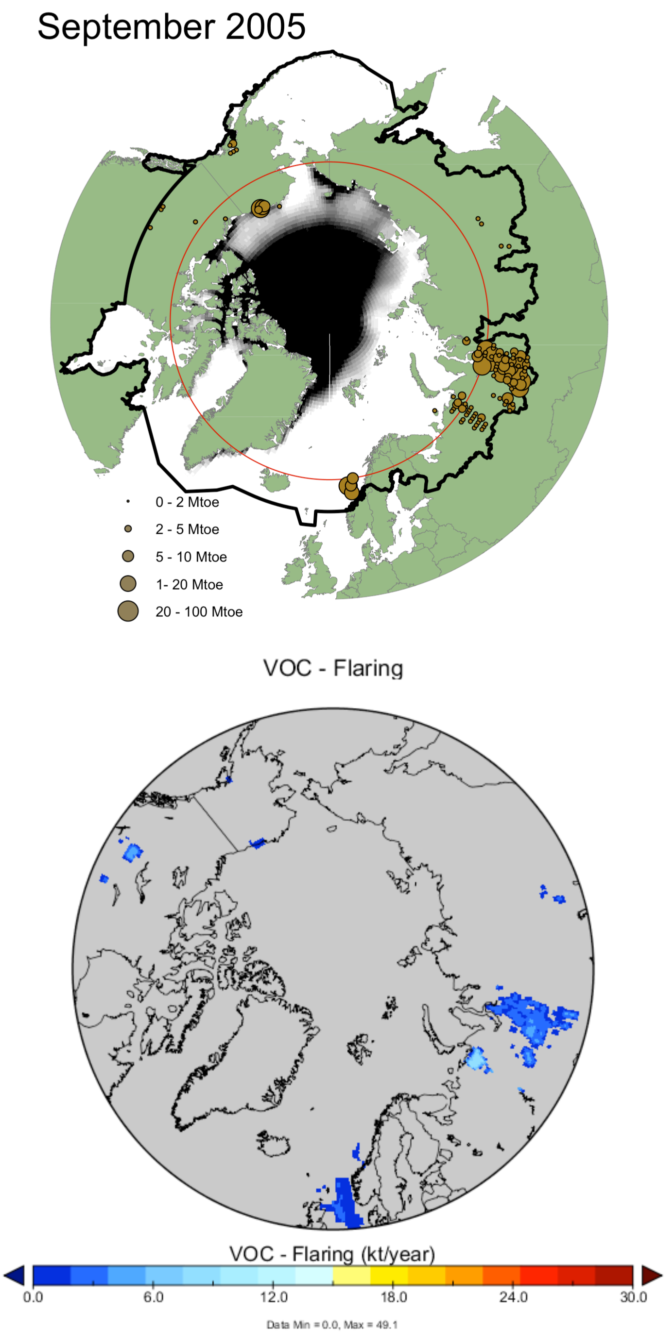

Figure 6a *– top: production totals (Mton/yr) for 2005 associated with oil and gas extraction (courtesy G. Peters, based on Peters et al., 2011) and bottom: NMVOC flaring emissions (kt/yr) from IIASA GAINS ECLIPSE for 2011 (courtesy Z. Klimont)*

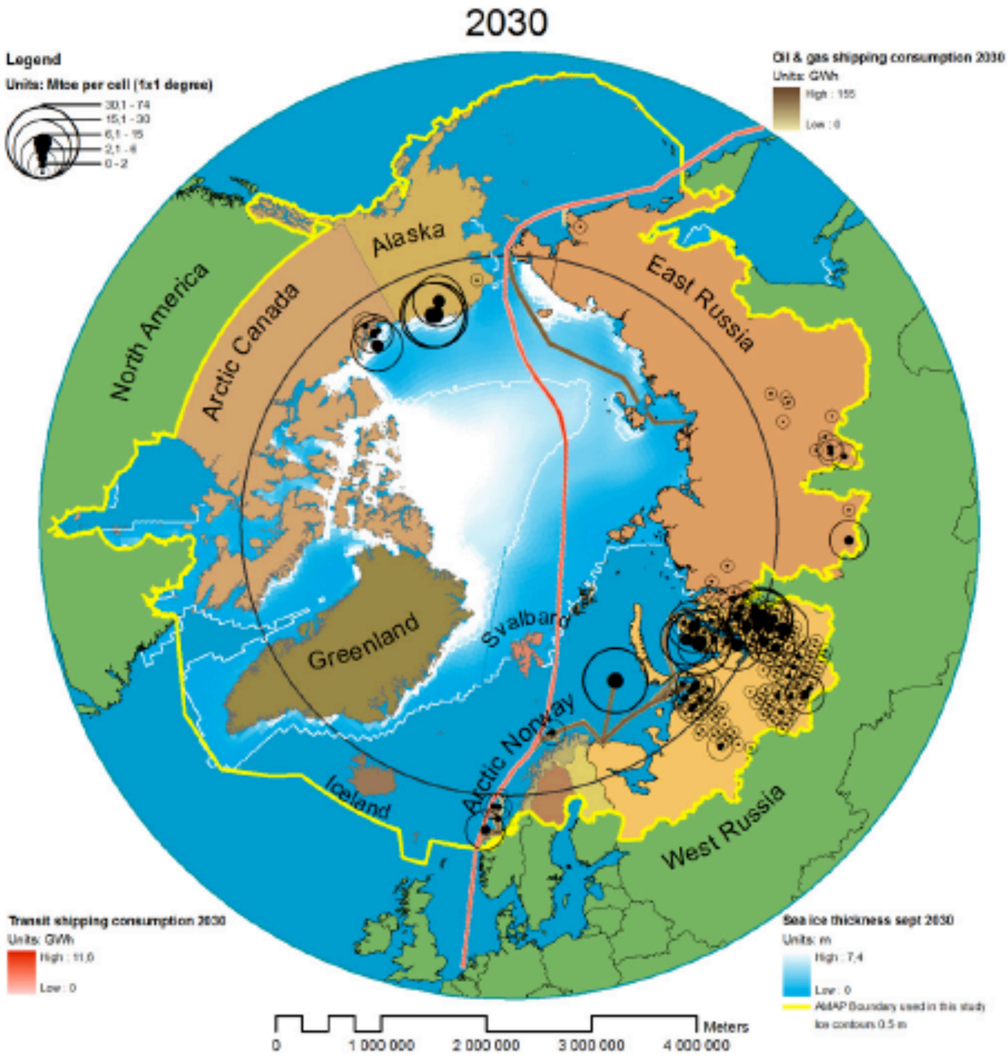

Figure 6b – *Projected future production estimates (Mton/cell) for 2030 associated with oil and gas extraction. From Peters et al. (2011).*

3. Gridded emissions reported for facilities in the Norwegian Sea

In this section we compare official estimates for a series of facilities in the Norwegian Sea including those associated with the Heidrun field (Figure 7). The Heidrun field was the focus of flights around oil/gas platforms during the ACCESS campaign in July 2012.

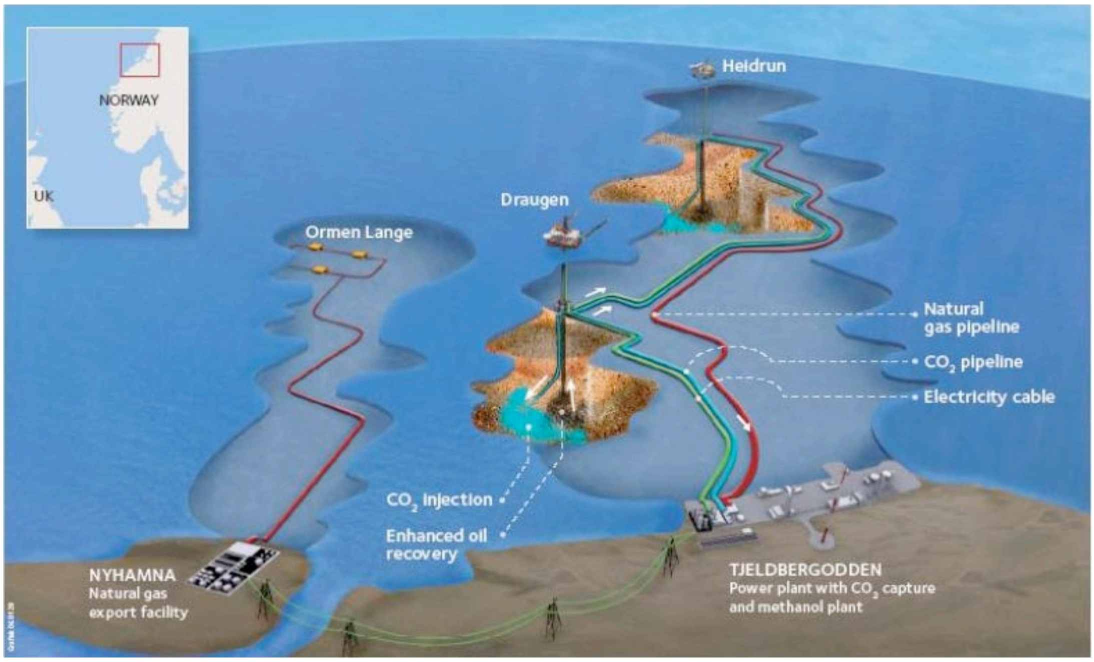

Figure 7 *– Schematic of the Heidrun platform setup (http://www.globalsecurity.org).*

The Heidrun field is in the Haltenbanken region on the Norwegian continental shelf at 190km from the coast and at a depth of 230m. The oil and gas reservoirs are situated at a depth of approximately 2300m. Extraction is performed using pipelines with 56 drilling sites including 51 production sites, 4 sites for water injection and one for gas injection. Heidrun's oil reserves are estimated to contain 750 million blue barrels (bbl) or 119 million m^3 (1 bbl equals 0.159 m^3). The gas reserves associated with this field are estimated to hold 1.77 Tcf (trillion cubic feet) equivalent to 28 million m^3. The oil extracted from this field is transferred by ship to pipelines which then transport the oil to refineries on the Norwegian coast.

Emission estimates reported by facility are available from the European Pollutant Release and Transfer Register (E-PRTR) online at http://prtr.ec.europa.eu/ and are summarized in Table 2 for selected offshore facilities in the Norwegian Sea including Heidrun. E-PRTR is the Europe-wide register that provides key environmental data from industrial facilities located in European Union Member States (as well as for Iceland, Liechtenstein, Norway, Serbia, and Switzerland). The register contains data reported annually for 28,000 industrial facilities covering 65 economic activities across Europe, including industrial oil extraction.

The goal of the on-going ACCESS work is to use the measurements made during July 2012 to evaluate these reported emissions. Currently, the operators of these facilities are required to provide the best available data on their facilities' pollutant releases for the purposes of European reporting, which are typically not measured directly. However, very few independent methods of checking emissions exist and the ACCESS campaign provides one opportunity to evaluate emissions. A common approach is to measure fuel composition and the amount of used fuel gas, flare gas and diesel (Statoil, personal communication). The expected emissions can then be calculated with the help of standard industry emission factors. However, very few independent methods of checking emissions exist and the ACCESS campaign provides one opportunity to evaluate emissions from extraction activities. One complication is that some facilities in reality are composed of many single installations, for example Åsgard. However, their emissions are reported only as point source emissions at one single location (see discussion later in Section 4 and Figure 9 and 10). Therefore, future work will include recommending distributing emissions onto multiple point sources based on the measurements.

***Table 2** – Reported emissions available from the European Pollutant Release and Transfer Register for oil/gas facilities in the Norwegian Sea, the focus of the ACCESS aircraft campaign.*

Facility	Main activity	Lat, Lon	Year	Chemical Compound	Emissions (tonnes/year)
Åsgard	Extraction of crude petroleum	6.725545°, 65.06417°	2009	Methane	5,920
				NMVOC	6,950
				NO_x	1,990
			2010	Methane	4,750
				NMVOC	6,300
				NO_x	1,690
Heidrun	Extraction of crude petroleum	7.315686°, 65.32562°	2009	Methane	493
				NMVOC	435
				NO_x	1,950
			2010	Methane	393
				NMVOC	319
				NO_x	1,590
Norne	Extraction of crude petroleum	8.086531°, 66.02713°	2009	Methane	343
				NMVOC	444
				NO_x	1,050
			2010	Methane	327
				NMVOC	441
				NO_x	1,530

4. Description of aircraft campaign and measurements

Within the framework of the ACCESS project, an aircraft campaign was conducted during three weeks in July 2012. The research aircraft DLR Falcon was based in Andenes, northern Norway, from 09th to 27th July. 13 scientific flights aimed to study the chemical and aerosol composition of the Arctic (see Figure 8). Thereby emissions and distributions of trace compounds were measured including nitrogen oxides, hydrocarbons, sulphur dioxide, and particulate matter (e.g. black carbon). The main objective of the aircraft campaign was to analyse the impact of different pollution sources on the Arctic, with a special focus on oil/gas platform and ship emissions since these activities are foreseen to increase in the future. Two flights were dedicated to study oil and gas platform emissions in the Norwegian Sea. These were performed in close collaboration with the Statoil oil company. One flight aimed to measure emissions of different types of oil/gas facilities in the Norwegian Sea (production platforms, storage vessels, drilling rigs). Figure 9 shows the view out of the Falcon cockpit while approaching the platforms in the Norwegian Sea. According to Statoil, most of the facilities were in normal operation mode during the time of our measurements (personal communication, Statoil). The objective of the second flight was to study the dynamical and chemical evolution of emissions from a single installation (the "Heidrun" platform).

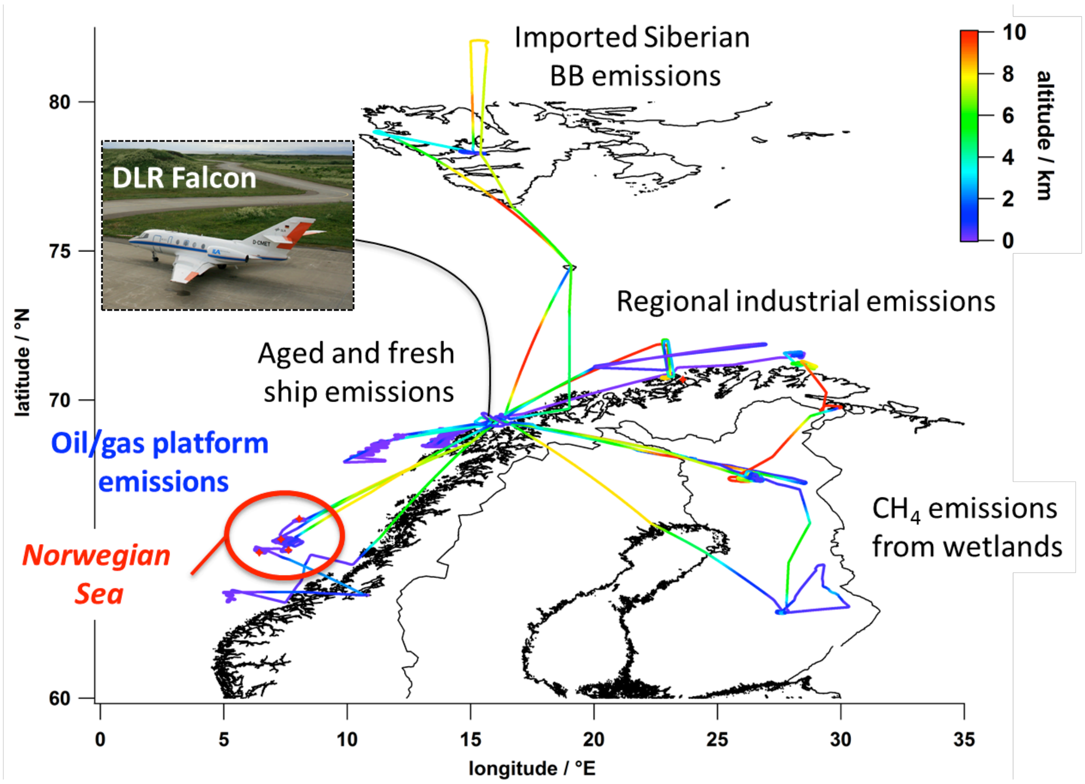

***Figure 8** – DLR Falcon flight tracks of all 13 scientific ACCESS flights, each of which was dedicated to a different kind of pollution source. The two research flights on 19th and 20th July 2012 focused exclusively on the measurement `of oil/gas platform emissions in the Norwegian Sea.*

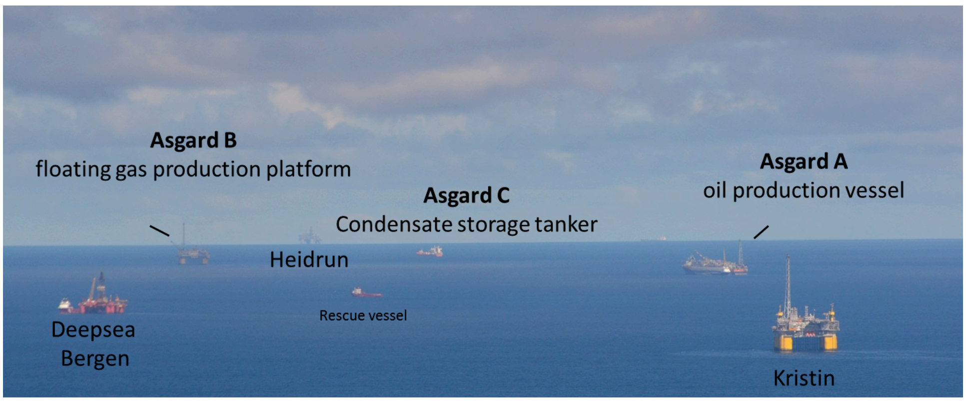

***Figure 9** – Cockpit view of Falcon during approach to oil facilities in the Norwegian Sea (picture taken on 19th July 2012, Stefan Grillenbeck, DLR).*

The Falcon flight path of the 19th July flight is given in Figure 10. During this flight, the emissions of different kind of oil and gas facilities were probed, including production platforms (e.g. Asgard A, C, Heidrun), storage tankers (e.g. Randgrid), as well as drilling rigs

(Deepsea Bergen, Transocean Spitsbergen). In addition, a lot of ship traffic was observed in the platform area. The flight path is colour-coded by measured nitrogen monoxide (NO), showing clear enhancements downstream of all facilities. Due to the north-westerly winds prevalent on this day, the emissions are sampled south-west of the installations. Two or more plume samples were taken downstream of each facility, at different distances and/or altitudes.

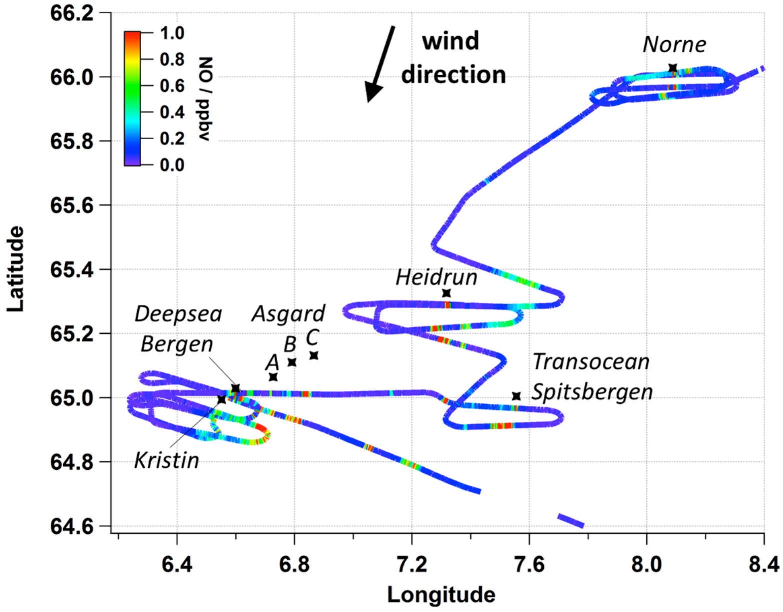

***Figure 10** – Falcon flight track on 19th July 2012. After take-off in Trondheim, the Falcon flew-by at different kind of facilities in the Norwegian Sea, the Heidrun region. The flight path is colour-coded by the measured concentration of nitrogen monoxide (NO).*

First data analysis reveals clear differences in the chemical and aerosol compositions for different facilities. Oil/gas production platforms (e.g. Heidrun and Åsgard B), which operate mainly on fuel gas, emitted low levels of SO_2 and mostly volatile particles (non-volatile particle fractions < 10%). In those plumes, a significant increase in the nucleation mode particle concentration (up to 50% of total particle concentration) was observed. This suggests new particle formation in the plumes, possibly due to high levels of co-emitted VOCs. Emissions from a shuttle tanker and a condensate storage tanker (Åsgard C and Randgrid) operating on fuel oil were characterised by high SO_2 concentrations and high fractions of non-volatile particles (>45%). Drilling rigs (Deepsea Bergen, Spitsbergen) released moderate levels of SO_2 but also high number of non-volatile particles.

Further data analysis will focus on the comparison of measured quantities of different exhaust gases and aerosols with values reported in emission inventories (see section 2) and official emission estimates (see section 3). In this case, the atmospheric dilution has to be taken into account since the plume gets dispersed after being emitted into the atmosphere.

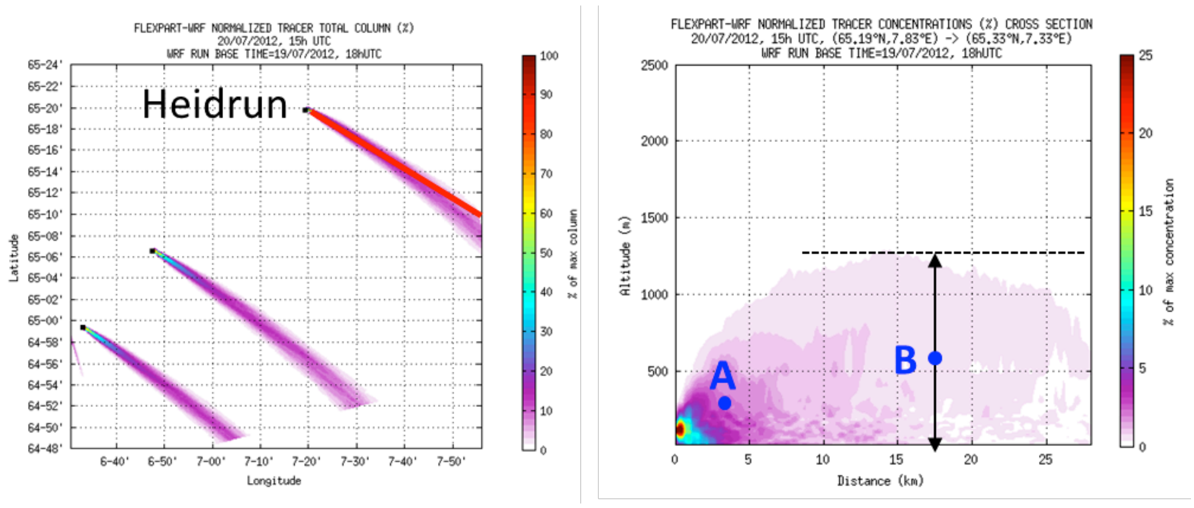

***Figure 11** – Heidrun plume location forecasted by the FLEXPART-WRF model on 20 July 2012. Left: top view of the predicted plume location. Right: Cross section along red line in left figure, predicted vertical extent of emissions as a function of distance to the Heidrun platform. For more details see text.*

For that reason, the total flux of a certain species can be derived from a plume transect only if the atmospheric dispersion is known (and the species is conserved, i.e. no removal processes were active until the time of the measurement). In order to calculate absolute mass fluxes from the different plume transects illustrated in Figure 10, we will use two independent approaches to determine plume dilution. For plume samples close to the emission source (see e.g. point A in Figure 11 right), the emissions are still inhomogeneously distributed (~ i.e. within the first 10 ~ 15 km). We will use estimates of the rates of atmospheric dilution predicted by the FLEXPART-WRF model as a method to determine source emissions using measurements made at different distances from the platforms.

For plume transects farther away, the emissions are assumed to be uniformly distributed within the boundary layer (see e.g. point B in Figure 11 right). In these cases, we can use the well-established “mass balance approach” (e.g. Ryerson et al., 2011). According to this, the flux of a conserved species X can be calculated across a plane defined by a plume transect of an aircraft and perpendicular to the wind direction:

$$\text{Net flux}(X) = v \bullet \cos\alpha \bullet \int n(z)\,dz \bullet \int \text{mixing ratio } X(y)\,dy.$$

wherein *X* represents the species to be measured, *v* the wind speed, α the wind angle, *n* the atmospheric density, *z* the boundary layer height and *y* the plume width.

For this approach, several assumptions have to be made, e.g. that wind speed and direction as well as platform emissions were constant during the time of our measurements. However, the use of two different methods will allow us to independently derive mass fluxes for each plume transects and discuss associated uncertainties.

5. Emissions from flaring activities & future perspectives

There are currently substantial uncertainties regarding the volume of gas flared during oil/gas extraction and the magnitude of emissions associated with this gas flaring. Current estimates of gas flaring volumes rely on voluntary reporting made by corporations and individual countries. There is very little independent data on gas flaring volumes and it is known that some of the reported volumes are low. Estimates of gas flaring volumes have been determined by Elvidge et al. (2011) on the basis of satellite sensor observations across a series of years from 1995 through 2010. Figure 12 shows the estimated volume of gas flared (in billions cubic meters) from 1994 to 2010, using a combination of data provided by five satellites (Elvidge et al., 2011).

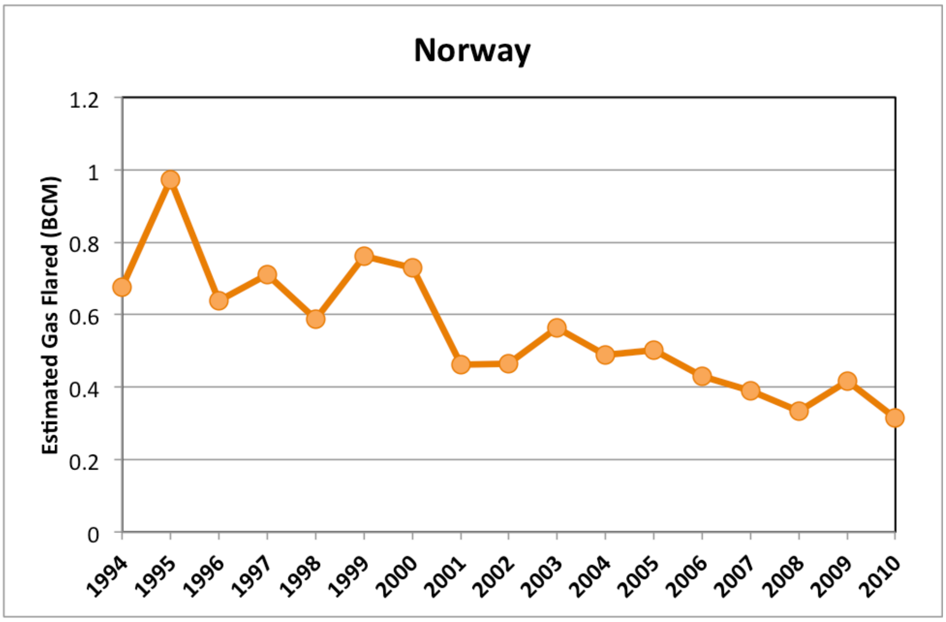

Figure 12 – *Estimates of gas flaring volumes for Norway based on Elvidge et al. (2011). Data available at: http://www.ngdc.noaa.gov/dmsp/interest/gas_flares_countries2.php?c=Norway*

For example, the recently developed IIASA-ECLIPSE (Evaluating the CLimate and Air Quality ImPacts of Short-livEd Pollutants) project emission have been developed with the GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model (Amann et al., 2011 and http://gains.iiasa.ac.at). For gas flaring in the oil and gas industry, GAINS relies on the time series of gas flaring volumes and spatial allocation developed within the Global Gas Flaring Reduction initiative (Elvidge et al., 2011, discussed above). Emission factors applied in GAINS draw on a number of measurements performed on industrial or lab-scale flares. A recent study notes that the lack of field measurements upon which BC emission factors can be based making estimates of BC from flaring highly uncertain (Stohl et al., 2013).

Therefore in the future, we will use the data of night-time lights (Figure 12, together with a map of night time lights provided to us by the DMSP satellite group (Oda et al., personal communication)). These data will be extrapolated to 2013, to estimate the amount of gas flared in Norway, and more specifically for the Heidrun platform, in 2012 when the campaign took place.

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