Atmos. Chem. Phys. Discuss., 11, 4913–4951, 2011
www.atmos-chem-phys-discuss.net/11/4913/2011/
doi:10.5194/acpd-11-4913-2011

Atmospheric Chemistry and Physics Discussions

Future emissions from oil, gas, and shipping activities in the Arctic

G. P. Peters[1], T. B. Nilssen[2], L. Lindholt[3], M. S. Eide[2], S. Glomsrød[1,3], L. I. Eide[2], and J. S. Fuglestvedt[1]

[1]Center for International Climate and Environmental Research – Oslo (CICERO), PB 1129 Blindern, 0318 Oslo, Norway
[2]Det Norske Veritas, Veritasveien 1, 1322 Høvik, Norway
[3]Statistics Norway, Postboks 8131 Dep, 0033 Oslo, Norway

Received: 20 December 2010 – Accepted: 31 January 2011 – Published: 9 February 2011

Correspondence to: G. P. Peters (glen.peters@cicero.uio.no)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The Arctic sea-ice is retreating faster than predicted by climate models and could become ice free during summer this century. The reduced sea-ice extent may effectively "unlock" the Arctic Ocean to increased human activities such as transit shipping and expanded oil and gas production. Travel time between Europe and the north Pacific Region can be reduced by up to 50% with low sea-ice levels and the use of this route could increase substantially as the sea-ice retreats. Oil and gas activities already occur in the Arctic region and given the large undiscovered petroleum resources increased activity could be expected with reduced sea-ice. We use a detailed global energy market model and a bottom-up shipping model with a sea-ice module to construct emission inventories of Arctic shipping and petroleum activities in 2030 and 2050. The emission inventories are on a 1×1 degree grid and cover both short-lived pollutants and ozone pre-cursors (SO_2, NO_x, CO, NMVOC, BC, OC) and the long-lived greenhouse gases (CO_2, CH_4, N_2O). We find rapid growth in transit shipping due to increased profitability with the shorter transit times compensating for increased costs in traversing areas of sea-ice. Oil and gas production remains relatively stable leading to reduced emissions from emission factor improvements. The location of oil and gas production moves into locations requiring more ship transport relative to pipeline transport, leading to rapid emissions growth from oil and gas transport via ship. Our emission inventories for the Arctic region will be used as input into chemical transport, radiative transfer, and climate models to quantify the role of Arctic activities in climate change compared to similar emissions occurring outside of the Arctic region.

1 Introduction

The Arctic is now experiencing some of the most rapid climate changes on earth. After 2000 yr of Arctic cooling, the trend was reversed in the 20th century (Kaufman et al., 2009) with temperatures now rising at approximately twice the rate of the rest of the

ACPD
11, 4913–4951, 2011

world with an acceleration of these trends projected in the coming century (ACIA, 2005; IPCC, 2007a). Melting glaciers, reductions in extent and thickness of sea-ice, thawing permafrost and rising sea level are indications of a recent warming in the region (Serreze et al., 2007). Observations over the past 50 yr show a decline in Arctic sea-ice extent throughout the year, with the most prominent retreat in summer (Serreze et al., 2007). Some analysts have suggested that the Arctic may be ice free in September as early as 2030 (Wang and Overland, 2009), though others suggested 2066–2085 (Boé et al., 2009). The melting of Arctic sea-ice will effectively unlock the Arctic Ocean, leaving it increasingly open to human activity – particularly oil and gas extraction and shipping.

With the expected increase in global demand for oil and decrease in production in certain areas (IEA, 2008), there may be enhanced pressure to expand oil and gas activities in the Arctic. While production in some Arctic oil and gas fields has declined, other discoveries have been made (AMAP, 2010). The Russian Shtokman field in the Barents shelf, one of the world's biggest known offshore gas fields, is currently being considered for development. Furthermore, it is reported that over one-fifth of the world's total undiscovered petroleum resources lies north of the Arctic Circle (Gautier et al., 2009). Together with technology improvements, decreased sea-ice extent may increase access allowing further exploration and eventual extraction of oil and gas in the Arctic Ocean.

Increased melting of the Arctic sea-ice may also open new possibilities for shipping routes and extended use of existing routes (Paxian et al., 2010). The seaborne cargo along the Northern Sea Route (NSR) has previously been very limited (Paxian et al., 2010; PAME, 2009) and the reported ship emissions low (Paxian et al., 2010; Corbett and Koehler, 2003; Endresen et al., 2003; Dalsøren et al., 2009). Recent trends indicate longer seasons with less sea-ice cover and reduced thickness (Serreze et al., 2007; Boé et al., 2009), implying improved ship accessibility around the margins of the Arctic Basin. Climate models project an acceleration of this trend and opening of new shipping routes and extension of the period during which shipping is feasible

ACPD
11, 4913–4951, 2011

(ACIA, 2005; Boé et al., 2009). One set of projections estimate that the navigation season (defined as 25% open water and 75% sea-ice cover) for the NSR may increase from the current 70 days pear year, to 125 days mid-century, and over 160 days in 2100 (ACIA, 2005, Chapter 16). Ships with ice-breaking capability may extend the navigation season even further. Travel time along the NSR between Europe and the north Pacific Region can be reduced by up to 50%, compared to current sea routes giving large potential transport cost savings (Khon et al., 2010; FNI, 2000). However, the extent to which the NSR is used will depend on a trade-off between reduced travel time and the increased costs and risks of shipping in Arctic conditions.

The potential increase in Arctic activities and emissions will not only have an impact on the global climate, but may also increase local warming trends. Several studies have shown that the forcing and temperature response can be dependent on the location of emissions (e.g., Berntsen et al., 2006; Shindell and Faluvegi, 2009; Hansen et al., 2005), but the sensitivity of the Arctic to regional emissions is not well known. Short-lived pollutants are found to be relatively important for the Arctic and could explain some of the recent warming compared to the global average (Quinn et al., 2008; Shindell and Faluvegi, 2009; Hansen et al., 2005). Both emissions occurring within the Arctic and those transported from outside the Arctic are found to be important (Quinn et al., 2008) and emissions at mid-latitudes can also cause changes in the meridional transport of heat to the Arctic (Shindell and Faluvegi, 2009). In addition, mechanisms such as black carbon deposition on snow or ice could also increase local warming trends through a decrease in the snow and ice albedo (ACIA, 2005; Hansen and Nazarenko, 2004; Flanner et al., 2007; Rypdal et al., 2009). Currently there are no detailed bottom-up emission inventories specific to the Arctic region that would allow, in particular, a comparison of the climatic impacts of activities located in the Arctic compared to those same activities occurring outside of the Arctic. To facilitate future impact assessments it is necessary to produce specific emission inventories for the Arctic region.

A basis for this paper is that decreased sea-ice in the future Arctic Region will "unlock" the Arctic Ocean to expanded activities. We develop an emission inventory for

ACPD
11, 4913–4951, 2011

the Arctic for the present (2004) and scenarios for 2030 and 2050. As the inventories will be input into chemical transport, radiative forcing, and climate models, they will be determined on a 1 × 1 degree grid and cover both short-lived pollutants and ozone precursors (SO_2, NO_x, CO, NMVOC, BC, OC) and the long-lived greenhouse gases (CO_2, CH_4, N_2O). The activities considered will be oil and gas production and shipping. The oil and gas inventory includes emissions from oil and gas production and from oil and gas transport by ship. The shipping inventory includes transit shipping across the Arctic Ocean but the Northern Sea Route is also considered. The use of the North West Passage (NWP) for fishing and other shipping activities is not considered, because channels suited for large ships are likely to continue to have difficult ice conditions for many years ahead (Wilson et al., 2004). The emission inventories will be the basis for an analysis of the climate impacts of unlocking the Arctic Ocean to future activities.

The paper is structured as follows: first, we describe the current activities in the Arctic region with some indications of how they have changed in the past. Second, we describe the current and possible future sea-ice extents which make the basis for the activity levels in 2030 and 2050. Third, the majority of the paper will focus on the development of the activity levels for the predicted sea-ice extent and the emission levels based on those activities. The paper will close with a discussion of the results and implications for modelling.

2 Current Arctic activities

2.1 Defining the Arctic region

The Arctic region has a variety of physical, geographical, and ecological characteristics which may lead to different definitions of the Arctic region. Definitions could extend to the approximate southern boundary of the midnight sun (Arctic Circle, 66°32′ N), climate boundaries such as the area north of a given constant mean temperature (isotherm), marine boundaries representing the convergence of different water masses, vegetation boundaries such as the tree line or transition between tundra and boreal forest, and political and administrative considerations. In this article we take an extended version of the definition used by the Arctic Monitoring and Assessment Programme that includes the entire administrative units where a territory is overlapping with the AMAP definition (AMAP, 1998; Glomsrød and Aslaksen, 2009), see Fig. 1. Our focus is on the Arctic Ocean, but we use a broader definition of the Arctic region to fully capture oil and gas activities that potentially requiring shipping in the Arctic Ocean.

2.2 Current oil and gas activities

Oil and gas activities began in the Arctic region around 1950 (AMAP, 2010; IHS Incorporated, 2009). There was rapid growth in oil and gas production until 1990 and the collapse of the former Soviet Union. Oil and gas production dropped to 80% of peak levels by mid-1990 and production has now returned to 1990 levels (Figs. 2 and 3). From 1990–2004, Arctic oil production was dominated by West Russia (79%) followed by Alaska (18%), Norway (3%), and small amounts in the other regions. Gas production was also dominated by West Russia (96%) followed by Alaska (3%) and small amounts from the other regions. Alaska, particularly Prudhoe Bay, extracts large quantities of gas which are later reinjected as it is too costly to get to market. Around one-half of cumulative Arctic production is oil (51%), with large regional differences: Canada (59% oil), Alaska (87%), East Russia (9%), West Russia (46%), and Norway (84%).

2.3 Current shipping activities

An extensive study of present ship activity in the Arctic was undertaken by PAME (2009). The study used 2004 as the base year and concluded that shipping activity was dominated by community re-supply, fishing and tourism. Community resupply is taking place along the NSR and NWP. Excluding ship traffic along the coast

ACPD
11, 4913–4951, 2011

of Norway and around Iceland, the bulk cargo is dominated by export from a few large mining operations in Alaska (zinc) and Russia (mainly nickel but also other minerals). Fishing mainly takes place in the ice-free waters around Iceland and in the Bering, Barents and Norwegian Seas, and tourism has its greatest intensity along the coasts of Northern Norway, Southwest Greenland and Svalbard (PAME, 2009). Transport of oil and gas by ships from the Arctic is limited and most of it takes place on the Eurasian side. Commercial transit traffic, except tourism, has taken place only along the NSR, which was opened to foreign ships in 1991 but after 1993 the traffic has been in steady decline. However, 2009 and 2010 saw renewed interest from Western companies to transit the NSR, reducing the journey between Ulsan (Korea) and Rotterdam by 4000 nautical miles (7400 km).

The estimate of 2004 shipping emissions in the Arctic was based on Dalsøren et al. (2009). Dalsøren et al. used an activity based approach to model global fuel consumption and emissions from all ships above 100 gross tonnes (GT), finding a total fuel consumption of 217 million tonnes (Mt) in 2004. The modelled fuel consumption and corresponding atmospheric emissions were distributed geographically on a 1 × 1 degree grid according to the relative number of ship observations in each cell. The ship observation data set used is a combination of the Comprehensive Ocean-Atmosphere Data Set (COADS) and the Automated Mutual Assistance Vessel Rescue System (AMVER) data with a total of 1 990 000 ship observations globally. COADS and AMVER data has been used separately by several studies to illustrate global traffic and emissions distributions (e.g., Corbett et al., 1999; Endresen et al., 2003; Eyring et al., 2005; Beirle et al., 2004) and are considered to be the most comprehensive global ship observation datasets available.

Using the distribution and fuel consumption and emission figures from Dalsøren et al. (2009), and the defined AMAP boundary used in this study (Fig. 1), we find that 6713 kt, or 3.1% of the global fuel consumption, is located within the AMAP region. We assumed that there was no transit shipping in 2004 and estimated the oil and gas shipping based on the oil tankers operating in the AMAP region (0.14% of

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
ACPD
11, 4913–4951, 2011
Future emissions in the Arctic
G. P. Peters et al.

global oil tankers). We consider that this estimate covers the activities described by PAME (2009).

3 Future activities in the Arctic

We now focus on future shipping activities and petroleum production in the Arctic region. While other activities are important in the Arctic (see the Supplementary material for a brief overview), shipping and petroleum production are most related to sea-ice coverage. In our modelling, the future shipping has strong dependence on the future sea-ice conditions. Petroleum production has higher production costs in the Arctic (though the costs are independent of the sea-ice scenarios), but the production locations are partially dependent on sea-ice coverage.

3.1 Future sea-ice conditions in the Arctic

Future ice conditions were extracted from the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM, Collins et al., 2006). The CCSM3 model was found to be closest to observations between 1972 and 2007 (Overland and Wang, 2007; Stroeve et al., 2007). This model gives a faster reduction of sea-ice cover than the mean of the five models that went into the ACIA assessment (ACIA, 2005, Chapter 16). Ice concentration and ice thickness for four CCSM3 runs were extracted for the years 2007 to 2100. To avoid random year-to-year variations and produce a smooth development of the future ice conditions a five year running average was used to calculate sea-ice conditions in March, June, September and December (representing each season) in 2030 and 2050. The sea-ice extent was defined as the area where ice concentration is larger than 15%. The modelled sea-ice extent was translated onto a 1 × 1 degree grid, thus ice is removed from all grid cells where the ice concentration is less than 15%. Monthly mean ice conditions were calculated by retaining the correct sea-ice concentration and sea-ice thickness in each cell, while at

ACPD
11, 4913–4951, 2011

the same time preserving the total sea-ice area (Eide et al., 2010). The future sea-ice extent in September used in this study for the years 2030 and 2050 is shown in Fig. 4.

3.2 Future oil and gas production in the Arctic

Currently, the Arctic produces about a tenth of the world's oil and a quarter of its gas (AMAP, 2008). While some fields are in decline, new discoveries are being made (AMAP, 2010) and there are considerable potential resources in the Arctic (Gautier et al., 2009). The United States Geological Survey (USGS) estimates that the area north of the Arctic Circle contains about 30% of the world's undiscovered gas and 13% of the world's undiscovered oil (Gautier et al., 2009) with the largest resources for Russian gas. Despite the large potential, it is not clear whether the Arctic will sustain its current contribution to global supply. To estimate future oil and gas production in the Arctic requires a global model that considers the estimated resources and production costs, together with assumptions on the oil price.

3.2.1 The FRISBEE oil and gas production model

The potential scale of future petroleum production in the Arctic regions is assessed based on the FRISBEE model of the global energy markets (Aune et al., 2009). The model was previously used for studies of impacts of petroleum industry restructuring (Aune et al., 2005) and globalization of natural gas markets and trade (Aune et al., 2010). More details of the model are found in the Supplementary material and only a brief summary is provided here.

The FRISBEE model describes future supply and demand of oil and gas through elaborate modelling of oil and gas investments and production. It is a recursively dynamic partial equilibrium model accounting explicitly for discoveries, reserves, field development and production of oil and gas. The emphasis is on petroleum markets; however, the global market for coal and regional markets for electricity are also modelled albeit in less detail. Production generally takes place in 15 regions and four field

ACPD
11, 4913–4951, 2011

categories depending on location onshore/offshore, depth of offshore fields and size of resources. For each Arctic region, see Fig. 1, the model depicts one field category only. The process of discovering reserves from the pool of undiscovered resources is determined by expected oil or gas prices, field characteristics and the amount of remaining undiscovered resources. The model covers both conventional and unconventional resources.

For Arctic regions the time lag from investment decision to maximum plateau production is generally 50–100% longer than in comparable non-Arctic fields. Capital and operational costs in new Alaskan fields are assumed to be 50% higher than average costs of existing fields. For Norway, the costs of new fields are set to 50% above the cost level of the most expensive field category and Arctic Canada is assumed to have the same costs as Arctic Norway. The cost level in West Arctic Russia is also set to 50% over existing average cost level for this region, whereas costs in East Arctic Russia are twice the existing average cost level. Investment costs are assumed to increase over time as the undiscovered resources are being developed.

Arctic and other non-OPEC suppliers respond to the oil price level. The world market price of oil is exogenous in the model and OPEC satisfies the residual demand at the prevailing oil price, determined as the difference between world demand and non-OPEC supply. If demand rises due to income growth OPEC will increase supply to cover additional demand and keep the oil price at the preferred level of the cartel, however, Arctic and other non-OPEC supply remains unaffected as the price is constant. In the gas markets, however, the price is endogenous. The global oil and gas industry outside OPEC is modelled as separate investors allocating a share of the annual cash flow to fields by maximizing net present value of returns. Price expectations are based on adaptive expectations, assuming future prices will equal average of prices over the last 6 yr. The gas price is endogenously determined in regional markets. However the model depicts the gas market as global and integrated, separated by costs of transportation that have declined, in particular for LNG, and tend to harmonize regional prices over time.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
11, 4913–4951, 2011

Future emissions in the Arctic

G. P. Peters et al.

At the time of the study, the FRISBEE model did not include activity in Greenland. The production in Greenland was assumed to be zero in 2030 and increase linearly to a value in 2050 that was based on the size of the undiscovered resources (Gautier et al., 2009) and average extraction rates (IHS Incorporated, 2009). This is explained further in the section on the emission estimates.

3.2.2 Oil and gas output from 2000–2050

Figure 2 shows the future oil production for three oil price scenarios and Fig. 3 shows the future gas production.

Exploration and drilling cost are three to five times higher in the Arctic than in other petroleum provinces and thus depending on the oil price production may vary greatly in the Arctic. Figure 2 shows the effects on Arctic oil production when future oil prices (in 2005 USD) rise to $120 per barrel oil equivalent (boe) or declines to $40/boe. Total accumulated oil production is around 27% higher in the $120/boe scenario than in the reference scenario. The relative increase in production is higher in Russia than in the other Arctic regions. Total accumulated oil production in the $40/boe scenario is around 39% lower than in the reference scenario with similar reductions in relative terms across regions. In either case, even with a high oil price, FRISBEE does not estimate a significant increase in oil production in the Arctic.

Figure 3 shows estimated Arctic petroleum production from 2000 to 2050 with an oil price of $80/boe. There is a gradual decline in total production until 2030 before a slight increase towards 2050. Production is dominated by West Russia with strong growth in production in Alaska and Canada, and after 2030 in East Russia and Norway. As the price is endogenous in the gas modelling, we do not have different scenarios based on the oil price.

In our modelling of emissions we use the reference scenario ($80/boe). In the reference scenario, half of the total accumulated future Arctic production (2000–2050) is oil with large regional differences. Future Arctic oil production as a share of total accumulated production is 67% for West Russia, 21% for Alaska, 5% Norway, and 3.5%

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD
11, 4913–4951, 2011

Future emissions in the Arctic

G. P. Peters et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

for Arctic Canada and East Russia. Future cumulative Arctic gas production is 90% for West Russia, 4% for Norway, 3% Alaska, and 2% for Arctic Canada with smaller amounts in East Russia and Greenland. Over the time period 2000–2050 there is a slight shift of production from gas to oil (40% oil in 2000, 51% in 2050), though the cumulative split is roughly 50%.

In another study Wood Mackenzie focused on oil and gas production in the Arctic (Wood Mackenzie and Fugro Robertson, 2006). It is difficult to compare our results with theirs, as there are differences in geographical definitions and petroleum price assumptions. Wood Mackenzie claims to take profitability into consideration, however, to what extent is not made clear in published material. The petroleum supply from the Arctic region as a whole would, according to Wood Mackenzie, peak around 2030 at 400 Mtoe (8 million barrels of oil equivalents per day) with 40% oil and 60% gas in the most likely scenarios. In addition, Wood Mackenzie depicts a more optimistic scenario for future production where petroleum supply will peak at over 700 Mtoe in 2030 (30% oil and 70% gas). Our oil reference production level in 2030 is much higher than their most likely level. However, when we apply a low oil price of $40/boe our production level in 2030 is around 25 percent lower than theirs. Our reference Arctic gas production level in 2030 is close to the average of their reference level of 239 Mtoe and their optimistic level of 483 Mtoe in 2030.

3.2.3 Production locations

The FRISBEE model gives oil and gas production in 2030 and 2050 for East Russia, West Russia, Alaska, Arctic Canada, and Arctic Norway. The FRISBEE output is then allocated to a 1×1 grid using data provided by IHS (IHS Incorporated, 2009) and USGS (Gautier et al., 2009). The IHS data contains gridded data on historic oil and gas production, estimated resources, and additional data such as stage of production, on/off-shore, and so on. The USGS Arctic appraisal contains estimates of undiscovered resources in the Arctic. A brief overview of the gridding method is given here, with more details in the Supplementary material.

ACPD
11, 4913–4951, 2011

The gridding is performed in a three step process: first, average cumulative extraction rates are estimated for each field; second, the fields operating in each year are determined; and third, the total extraction in each region is scaled to match the FRISBEE output. In the first step, the average cumulative extraction rates (cumulative production divided by years in production) for each field are determined using either historic production data or resource size for the fields not currently in production using the IHS data (IHS Incorporated, 2009). In the second step, using information on the current stage of development in each field (IHS Incorporated, 2009), fields are selected that are in operation in either 2030 or 2050. In the third step, the estimated extraction rates in 2030 and 2050 are then scaled so that the regional output matches the FRISBEE model output. The USGS data on undiscovered resources (Gautier et al., 2009) are incorporated in the 2050 estimates. Greenland is not included in the FRISBEE results and the output is estimated using the estimated field size.

We are not aware of other studies that provide oil and gas output in the Arctic at this level of spatial detail (1×1 degree grid). The gridding for 2030 and 2050 is based on current areas of exploration, but many of the undiscovered resources are in or adjacent to existing areas of production (Wood Mackenzie and Fugro Robertson, 2006). For 2050, we use estimated resources which cover large geographic areas (Gautier et al., 2009; IHS Incorporated, 2009) and we visually selected grid points for future production in each of the USGS Assessment Units. We only place production at realistic and accessible locations (see Supplementary material and Murray, 2006). A consequence of the gridding methodology is that future production locations are more distributed than current production locations (Fig. 4). In practice future activities may be more centralized, however, without better information we keep the information as estimates can be grouped to centralized grid-points if needed.

3.3 Oil and gas emissions

We use the common Tier 1 approach to constructing emission inventories (IPCC, 2006), based on the relationship Emissions = Emission Factor · Activity. The following

ACPD
11, 4913–4951, 2011

sections outline the emission factors, followed by the emission levels under the different scenarios. We focus on climate relevant species (IPCC, 2007b) covering both long-lived greenhouse gases (CO_2, CH_4, and N_2O) in addition to short-lived pollutants and ozone precursors (SO_2, NO_x, CO, NMVOC, BC and OC).

3.3.1 Emission factors

As output from our model of oil and gas activities we have the volume of oil and gas extracted at each 1×1 degree grid point in the Arctic. Thus, the emission factors are in units of emissions per unit oil/gas sold to market. The data on emissions per unit oil extracted is generally poor, particularly in some Arctic regions. As default values we use a global dataset based on voluntary reporting by oil and gas companies (Oil and Gas Producers, 2009) and update this using national statistics when possible. Most updates are obtained by dividing the total oil and gas emissions by the oil and gas extracted in each region. In the absence of better data, we use regionally averaged emission factors instead of attempting to estimate site-specific (gridded) emission factors. We base the emission factors on net oil and gas production (to market) and not gross production to be consistent with the FRISBEE model. There is very little variation in the emission factors for oil and gas extraction and for on- and off-shore extraction (Oil and Gas Producers, 2009), consequently, we assume that the emission factor per tonne oil-equivalent is the same for oil and gas extraction and for off- and on-shore facilities. Table 1 shows the emission factors used for 2004 with further details in the Supplementary material.

3.3.2 Aggregated emissions

Table 2 shows the emission estimates for 2004 calculated using the emission factors in Table 1 and the actual oil and gas production in 2004. As noted earlier, we base the emission factors on the net emissions (oil and gas to market), with the most significant effect for Prudhoe Bay in Alaska where most gas is re-injected due to the high cost of

ACPD
11, 4913–4951, 2011

transporting the gas to markets. Over the same area, the EDGARv3.2 database gives values of 8.0 Mt CO_2, 6743 kt CH_4, 14.5 t N_2O, 2531 kt NMVOC, 72.0 kt SO_2, 7.2 kt NO_x, and 163 kt CO (Olivier et al., 2005). The more recent EDGARv4 database has 5.7 Mt CO_2, 2654 kt CH_4, and 45.9 kt NO_x with the other components not available at the time of comparisons (European Commission, 2009). Except for CH_4 and NMVOC, our estimates are larger than other studies and there are two key explanations for this. First, we only use a bottom-up data based on the actual volume of oil and gas extracted and the emission intensities are based on the net volume extracted. In contrast, most global emission data sets, like EDGAR, are based on fuel consumption and averaged emission factors that are not specific to the oil and gas sector. Second, we only use detailed gridded data for oil and gas locations. Global datasets often have a mix of gridding proxies which may default to population-based gridding in the absence of more specific data and this may locate the emissions further south around population centres. In both cases, our approach is more directly related to the activity levels and locations in the oil and gas sector. We have lower estimates for CH_4 and NMVOC since we did not estimate leaks from oil and gas transport in our estimates. In the case of BC and OC, Bond et al. (2004) reported estimates of 22.5 kt BC and 26.3 ktvOC in the AMAP region, but this covers all sectors. Thus, it is expected that our estimates will be much lower. Overall, our emission estimates are generally higher than previous estimates, but this could be expected given the more detailed approach we have taken.

To estimate future oil and gas emissions we multiply the oil and gas output in 2030 and 2050 with the emission factors derived earlier. It could be expected that the emission factors improve over time with technological development, though, certainly in the case of long-lived GHG emissions, this seems not to be the case in the oil and gas sector (Oil and Gas Producers, 2009; Statistics Norway, 2010). In the case of long-lived GHG emissions, the reason the emission factors vary so little over time is probably a mix of two key factors: first, more energy is required to extract oil and gas as reservoirs become depleted; and second, the required increase in flaring will decrease CH_4 but increase CO_2. Other pollutants that are easier to control, such as NMVOC and

ACPD
11, 4913–4951, 2011

NO_x, are more likely to decrease as they are regulated under existing protocols (UNECE, 2005) and mitigation technologies are widely available. A key uncertainty in our analysis is what emission factors to use in 2030 and 2050. Since the data shows little improvement in emission factors over time we use two cases Table 2 and 3: first, a case where emission factors are kept constant at 2004 levels ("Constant Emission Factors"); and second, a "Best Practice Scenario" where it is assumed that all of the Arctic uses the lowest emission factor for each pollutant from 2004. For Greenland in 2050, we assume Norwegian emission factors as newer facilities are likely to use best available technology.

3.4 Future shipping activity in the Arctic

3.4.1 Methodology

Future Asia-Europe (A-E) traffic across the Arctic is estimated by modelling all A-E cargo flows to be covered by trade between one European port and three Asian ports; Rotterdam-Tokyo (R-T), Rotterdam-Hong Kong (R-HK) and Rotterdam-Singapore (R-S). Each port is a representation of a wider geographical area. Future Asia-Europe cargo volumes are estimated by translating the IPCC A2 scenario projections for global economic development into global seaborne trade volumes using the strong historical correlation between Gross Domestic Product (GDP) and seaborne trade, as reported by the EU project QUANTIFY (http://www.pa.op.dlr.de/quantify/) (Endresen et al., 2008). These global projections were then modified for use on the A-E trade. A-E cargo volumes are split equally between the three hubs, based on current trade statistics for the areas the hubs represent (European Commission, 2010) and assumptions of regional differences in the trade development. The resulting potentials for container traffic between Europe and Asia are 11.7 million TEU (3.9 million TEU per Asian hub) in 2030 and 16.7 million TEU (5.6 million TEU per Asian hub) in 2050. For each port pair (R-T, R-HK and R-S) and for each reference year (2030 and 2050) we then compare future voyage costs for Arctic transit against voyage cost for Suez transit. Two

ACPD
11, 4913–4951, 2011

alternatives for Arctic transit are investigated; year-round traffic using vessels designed for heavy ice condition, and summer transit using vessels designed for moderate ice. The voyage cost calculations includes fuel costs, explicitly modelling the effect of transiting ice, and additional construction costs for ice-strengthening. For each port pair, cargo volumes are then assigned to the most profitable route, which in turn gives the number of transits in 2030 and 2050. Potential gains from shorter transit times, such as higher freight tariffs, have not been explicitly included in the profitability calculations. However, shorter transit times translates to reduced fleet costs since fewer vessels are required to meet a given transport demand

We find that part-year Arctic transit will be commercially attractive for container traffic from the Tokyo hub in 2030 and 2050. The predicted amount of containers that will be transported through the Arctic equals 1.4 million TEU in 2030 (36% of the potential for the Tokyo hub) and 2.5 million TEU in 2050 (45% of the potential for the Tokyo hub). This corresponds to 480 transit voyages, or about 8% of the total container trade between Asia and Europe, in 2030 and 850 transits voyages, or about 10% of all container traffic between Asia and Europe, in 2050. The model has been tested with variations in fuel price and length of sailing season, and the conclusions presented are robust with regard to these factors (see Supplementary material). Future work with the model should extend this to include variations in other input factors like, choice of IPCC emission scenario, future ice scenario, ship concept, performance of the vessels in ice, cost of building and operating ice class vessels and alternative logistics, e.g., ice-strengthened vessels just for the Arctic Ocean and cargo transfer ports in the northern parts of the Pacific and Atlantic Oceans.

Shipping activity related to petroleum extraction has been estimated based on projected production data (described in the previous section). The fuel consumed by tanker vessels is modelled by assuming shipping routes and transhipment ports based on the production figures, and by combining this with the same model for fuel consumption as for transpolar shipping. For supply vessels a simplified statistical approach is used to correlate the amount of fuel consumed with the amount of petroleum

ACPD
11, 4913–4951, 2011

extracted, using statistics from the Norwegian Continental Shelf (Norwegian Petroleum Directorate, 2010). The results are sensitive to change in input variables such as the estimate of unproven resources, oil price, transportation mode and fluctuating oil and gas markets.

In total, the fuel consumption is 2880 kt in 2030 and 5180 kt in 2050 (Tables 5 and 6), covering transpolar container shipping, supply vessels and tankers transporting petroleum. However, it should be recognized that this study has not covered all Arctic ship emissions, such as from shipping activities related to tourism, local/national transport and fisheries. To our knowledge this is the first study that explicitly accounts for ship performance in ice to estimate the economic attractiveness of Arctic routes relative to the traditional Suez route for specific future ice scenarios. Other studies have assumed a percentage diversion of traffic (Corbett et al., 2010), a prolonged sailing season (Khon et al., 2010), or treated sea-ice as an impassable barrier (Paxian et al., 2010).

3.4.2 Emission factors

The emission factors (Table 4) used in this study are based on values of equivalent quantities for slow-speed engines running on residual fuel oil in the Second IMO GHG Study (Buhaug et al., 2009), except for particulates, which we based on Corbett et al. (2010). To allow for changing emissions in the future, due to e.g., international regulations and improvements in technology, we have introduced emission reduction factors. The emission factors improve over time according to a percentage "reduction factor" relative to the current emission factor based on the regulations of the International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 (MARPOL 73/78) which came into effect in May 2005 and the amendments of which came into effect 1 July 2010 (MEPC 176(58)).

ACPD
11, 4913–4951, 2011

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

3.4.3 Aggregated emissions

Table 5 shows the fuel consumption and the emissions resulting from transpolar shipping and shipping related to oil and gas-extraction in the Arctic in 2030 and 2050 (a split between petroleum and transit shipping is found in Table 6). These figures include emissions from container vessels on transpolar shipping routes, tankers transporting oil and gas, as well as supply vessels serving offshore installations in the Arctic. As noted earlier, shipping emissions from e.g., tourism, fishing and community resupply are not included in this table.

4 Discussion

Our analysis provides emission estimates for oil and gas extraction, and transit and oil and gas shipping in the Arctic region for 2030 and 2050. Table 6, Fig. 4 and Fig. 5 show a comparison of the emissions from the extraction of oil and gas, transit shipping, oil and gas shipping, and other shipping activities. The other shipping activities are based on an earlier study using ship observations in 2004 (Sect. 2.3) and in the absence of better data the same activity is assumed in 2030 and 2050. We based the other shipping emissions on the assumed improvements in emission factors (Table 4).

A comparison of the emissions from different activities in the Arctic indicates that emissions will not increase substantially above current levels (Table 6 and Fig. 5), though locations may change (Fig. 4). In 2004 the transit and petroleum shipping emissions were relatively small, requiring rapid growth to reach 2030 and 2050 levels. The rapid growth in the emissions from transit shipping occurs in locations that have not seen substantial emissions before (Fig. 4). However, compared to the business as usual case (no Arctic transit) there is a reduction in global fuel consumption in the shipping sector of 374 kt in 2030 and 932 kt in 2050 as the Arctic transit is shorter than shipping via the Suez Canal. The rapid growth in oil and gas shipping occurs despite relatively constant oil and gas production levels. This is since the sea-ice coverage

ACPD
11, 4913–4951, 2011

decreases and new fields are opened in off-shore locations requiring transportation by ship rather than the high levels of pipeline transportation currently in use (Bambulyak and Frantzen, 2009; Dalsøren et al., 2007). In terms of fuel consumption the shipping for oil and gas is around 50% higher than transit shipping, and other shipping is about twice the oil and gas shipping. In 2030 and 2050, emissions are dominated by petroleum production and other shipping (depending on the pollutant) suggesting relatively modest changes in aggregated emissions driven largely by emission factor improvements. Depending on the pollutant, different activities will dominate future emissions in the Arctic. Petroleum activities have higher emissions from energy use and flaring (CO_2 and CH_4), loading (NMVOC), and estimated particulates. Shipping has much higher emissions of NO_x, SO_2, CO and PM. Overall, the emissions are changing in volume, location, and source but we do not find a rapid aggregated emission increases in the Arctic region.

Estimating future activities in the Arctic is inherently difficult due to large uncertainties in sea-ice extent, resource availability, future economic development, and future policies. We assume that there are no political instabilities in the region allowing access to all Arctic resources (Brunstad et al., 2004) and we assume continued economic growth at the global level along the lines of the IPCC A2 scenario (Nakicenovic and Swart, 2000). We chose a sea-ice model that replicated the recent declines in sea-ice coverage better than other models, though it is unknown if these trends will continue (Boé et al., 2009; Amstrup et al., 2010). Our estimates of oil and gas extraction in the reference scenario are relatively constant seemingly contradicting the potential large increase in extraction based on the significant discovered resources in the Arctic Region (Gautier et al., 2009). However, our reference scenario produces greater oil and gas output than some other studies (Wood Mackenzie and Fugro Robertson, 2006). In addition to these issues there are considerable uncertainties in technological improvements, emission factors, oil price scenarios, economic growth, and so on. Our results should only be considered as an indication of potential emissions in the Arctic region. Both for oil and gas production and shipping, even with reduced summer sea-ice extent,

ACPD
11, 4913–4951, 2011

the Arctic will still be a challenging operating environment and our modelling suggests there will not be a rapid increase in Arctic emissions up to 2050.

5 Concluding remarks and further work

Our analysis has considered future activities and emissions in the Arctic region in 2030 and 2050 on a 1 × 1 degree grid and covering both short-lived pollutants and ozone pre-cursors (SO_2, NO_x, CO, NMVOC, BC, OC) and the long-lived greenhouse gases (CO_2, CH_4, N_2O). We find rapid growth in transit shipping due to increased profitability with the shorter transit times compensating for increased costs in traversing areas of sea-ice. Oil and gas production remains relatively stable in our scenarios leading to reduced emissions due to emission factor improvements. We find that the location of oil and gas production moves into locations requiring more ship transport relative to pipeline transport, leading to rapid growth in emissions from oil and gas transport by ship. Even though we do not find a significant increase in aggregated Arctic emissions, we do find a considerable change in the location of emissions. Studies have found that the forcing and climate response is dependent on the location of emissions and this may partially explain the more rapid recent warming in the Arctic compared to the global average. In future work studies using chemical transport, radiative transfer, and climate models will be used to help understand the forcing and climate response due to emissions occurring in the Arctic compared to those occurring outside of the Arctic.

Supplementary material related to this article is available online at: http://www.atmos-chem-phys-discuss.net/11/4913/2011/ acpd-11-4913-2011-supplement.pdf.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

ACPD

11, 4913–4951, 2011

Acknowledgements. Our analysis includes data supplied by IHS Inc., its subsidiary and affiliates companies; Petroconsultants S. A.; IHS data: Copyright (2011) all rights reserved. This work was funded by the Norwegian Research Council (project number: 184873/S30, "Unlocking the Arctic Ocean: The climate impact of increased shipping and petroleum activities (ArcAct)"). We thank Stig Dalsøren (CICERO) for help preparing the 2004 shipping estimates, Ole-Christian Ekeberg (DNV) for assistance with the data on sea-ice extent, Øyvind Espeland (DNV) for assistance with shipping in sea-ice conditions, Gjermund Gravir (DNV) for preliminary GIS work, Jonas Karstensen (CICERO) for preparing Fig. 4, and Terje Berntsen (CICERO and UiO) and Gunnar Myhre (CICERO) for helpful comments.

References

ACIA: Arctic Climate Impact Assessment, Cambridge University Press, 1042 pp., 2005.

AMAP: AMAP Assessment Report: Arctic Pollution Issues, Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 1998.

AMAP: Arctic Oil and Gas 2007, Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 2008.

AMAP: Assessment 2007 – Oil and Gas in the Arctic: Effects and Potential Effects, Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 2010.

Amstrup, S. C., DeWeaver, E. T., Douglas, D. C., Marcot, B. G., Durner, G. M., Bitz, C. M., and Bailey, D. A.: Greenhouse gas mitigation can reduce sea-ice loss and increase polar bear persistence, Nature, 468, 955–958, (http://www.nature.com/nature/journal/v468/n7326/abs/nature09653.html), 2010.

Aune, F. R., Glomsrød, S., Lindholt, S., and Rosendahl, K. E.: Are high oil prices profitable for OPEC in the long run?, Statistics Norway Discussion Papers 416, Oslo, 2005.

Aune, F. R., Rosendahl, K. E., and Sagen, E. L.: Globalization of Natural Gas Markets – Effects on Prices and Trade patterns, Energ. J., 30, 39–53, 2009.

Aune, F. R., Mohn, K., Osmundsen, P., and Rosendahl, K. E.: Industry restructuring, OPEC response – and oil price formation, Energ. Econ., 32, 389–398, 2010.

Bambulyak, A. and Frantzen, B.: Oil Transport from the Russian part of the Barents Region: Status per January 2009, The Norwegian Barents Secretariat and Akvaplan-niva, Norway, 97, 2009.

Beirle, S., Platt, U., von Glasow, R., Wenig, M., and Wagner, T.: Estimate of nitrogen ox-

ide emissions from shipping by satellite remote sensing, Geophys. Res. Lett., 31, L18102, doi:10.1029/2004gl020312, 2004.
Berntsen, T., Fuglestvedt, J. S., Myhre, G., Stordal, F., and Berglen, T. F.: Abatement of greenhouse gases: Does location matter?, Climatic Change, 74, 377–411, 2006.
Boé, J., Hall, A., and Qu, X.: September sea-ice cover in the Arctic Ocean projected to vanish by 2100, Nat. Geosci., 2, 341–343, 2009.
Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J.-H., and Klimont, Z.: A Technology-Based Global Inventory of Black and Organic Carbon Emissions from Combustion, J. Geophys. Res., 109, D14203, doi:10.1029/2003JD003697, 2004.
Brunstad, B., Magnus, E., Swanson, P., Hønneland, G., and Øverland, I.: Big oil playground, Russian bear preserve or European periphery? The Russian Barents Sea Region towards 2015, Eburon, Delft, 2004.
Buhaug, Ø., Corbett, J. J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D. S., Lee, D., Lindstad, H., Markowska, A. Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J. J., Wu, W., and Yoshida, K.: Second IMO GHG Study 2009, International Maritime Organization (IMO), 2009.
Collins, W. D., Bitz, C. M., Blackmon, M. L., Bonan, G. B., Bretherton, C. S., Carton, A., Chang, P., Donay, S. C., Hack, J. J., Henderson, T. B., Kiehl, J. T., Large, W. G., Mckenna, D. S., Santer, B. D., and Smith, R. D.: The Community Climate System Model Version 3 (CCSM3), J. Climate, 19, 2122–2143, 2006.
Corbett, J. J. and Koehler, H. W.: Update emissions from ocean shipping, J. Geophys. Res.-Atmos., 108, 4650–4666, 2003.
Corbett, J. J., Fischbeck, P. S., and Pandis, S. N.: Global nitrogen and sulfur inventories for oceangoing ships, J. Geophys. Res., 104, 3457–3470, doi:10.1029/1998jd100040, 1999.
Corbett, J. J., Lack, D. A., Winebrake, J. J., Harder, S., Silberman, J. A., and Gold, M.: Arctic shipping emissions inventories and future scenarios, Atmos. Chem. Phys., 10, 9689–9704, doi:10.5194/acp-10-9689-2010, 2010.
Dalsøren, S. B., Endresen, Ø., Isaksen, I. S. A., Gravir, G., and Sørgård, E.: Environmental impacts of an expected increase in sea transportation, with particular focus on oil and gas scenarios for Norway and northwest Russia, J. Geophys. Res., 112, D02310, doi:10.1029/2005JD006927, 2007.
Dalsøren, S. B., Eide, M. S., Endresen, Ø., Mjelde, A., Gravir, G., and Isaksen, I. S. A.: Update on emissions and environmental impacts from the international fleet of ships: the contribution

ACPD
11, 4913–4951, 2011

from major ship types and ports, Atmos. Chem. Phys., 9, 2171–2194, doi:10.5194/acp-9-2171-2009, 2009.
Eide, L. I., Ekeberg, O.-C., Solberg, K. E., and Valkonen, J.: Polarcross2 – Final Report, 2010.
Endresen, Ø., Sørgård, E., Sundet, J. K., Dalsøren, S. B., Isaksen, I. S. A., Berglen, T. F., and Gravir, G.: Emission from international sea transportation and environmental impact, J. Geophys. Res., 108, 4560, doi:10.1029/2002JD002898, 2003.
Endresen, Ø., Dalsøren, S., Eide, M., Isaksen, I. S., and Sørgård, E.: The environmental impacts of increased international maritime shipping, past trends and future perspectives, OECD/ITF Global Forum on Transport and Environment in a Globalising World, Guadalajara, Mexico, 2008.
European Commission: Emission Database for Global Atmospheric Research (EDGAR), release version 4.0 (http://edgar.jrc.ec.europa.eu), last access: 29 March 2010, Joint Research Centre (JRC) and Netherlands Environmental Assessment Agency (PBL), 2009.
European Commission: Top Trading Partners – Trade Statistics, (http://trade.ec.europa.eu/doclib/html/122529.htm), last access: 29 March 2010.
Eyring, V., Köhler, H. W., van Aardenne, J., and Lauer, A.: Emissions from international shipping: 1. The last 50 years, J. Geophys. Res., 110, D17305, doi:10.1029/2004jd005619, 2005.
Flanner, M. G., Zender, C. S., Randerson, J. T., and Rasch, P. J.: Present-day climate forcing and response from black carbon in snow, J. Geophys. Res., 112, D11202, doi:10.1029/2006jd008003, 2007.
FNI: Northern Sea Route Cargo Flows and Infrastructure – Present State and Future Potential, Fritjof Nansen Institute, 2000.
Gautier, D. L., Bird, K. J., Charpentier, R. R., Grantz, A., Houseknecht, D. W., Klett, T. R., Moore, T. E., Pitman, J. K., Schenk, C. J., Schuenemeyer, J. H., Sørensen, K., Tennyson, M. E., Valin, Z. C., and Wandrey, C. J.: Assessment of Undiscovered Oil and Gas in the Arctic, Science, 324, 1175–1179, 2009.
Hansen, J. and Nazarenko, L.: Soot climate forcing via snow and ice albedos, Proceedings of the National Academy of Sciences of the United States of America, 101, 423–428, doi:10.1073/pnas.2237157100, 2004.
Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, M., Bauer, S., Bell, N., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Del Genio, A., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Kelley, M., Kiang, N., Koch, D.,

ACPD
11, 4913–4951, 2011

Future emissions in the Arctic

G. P. Peters et al.

Lean, J., Lerner, J., Lo, K., Menon, S., Miller, R., Minnis, P., Novakov, T., Oinas, V., Perlwitz, J., Perlwitz, J., Rind, D., Romanou, A., Shindell, D., Stone, P., Sun, S., Tausnev, N., Thresher, D., Wielicki, B., Wong, T., Yao, M., and Zhang, S.: Efficacy of climate forcings, J. Geophys. Res., 110, D18104, doi:10.1029/2005jd005776, 2005.

IEA: World Energy Outlook 2008, International Energy Agency, 2008.

IHS Incorporated: International Petroleum Exploration and Production Database, IHS Incorporated, Englewood, 2009.

IPCC: IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, edited by: Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K., IGES, Japan, 2006.

IPCC: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., and Hanson, C. E., Cambridge University Press, Cambridge, UK, 976 pp, 2007a.

IPCC: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 996 pp, 2007b.

Kaufman, D. S., Schneider, D. P., McKay, N. P., Ammann, C. M., Bradley, R. S., Briffa, K. R., Miller, G. H., Otto-Bliesner, B. L., Overpeck, J. T., Vinther, B. M., and Arctic Lakes 2k Project Members: Recent Warming Reverses Long-Term Arctic Cooling, Science, 325, 1236–1239, doi:10.1126/science.1173983, 2009.

Khon, V. C., Mokhov, I. I., Latif, M., Semenov, V. A., and Park, W.: Perspectives of Northern Sea Route and Northwest Passage in the twenty-first century, Climatic Change, 100, 757–768, 2010.

Murray, A.: Arctic offers chilly welcome, E&P, 1 December 2006.

Norwegian Petroleum Directorate: Total gross production from the Norwegian Continental Shelf per year, (http://www.npd.no/engelsk/cwi/pbl/en/index.htm), last access: 4 June 2010, 2010.

Oil and Gas Producers: Environmental performance in the E&P industry – 2008 data, International Association of Oil & Gas Producers, Report No. 429, 2009.

Olivier, J. G. J., Aardenne, J. A. v., Dentener, F., Ganzeveld, L., and Peters, J. A. H. W.: Recent trends in global greenhouse gas emissions: regional trends and spatial distribution of key

sources, in: Non-CO2 Greenhouse Gases (NCGG-4), edited by: Amstel, A. v., Millpress, Rotterdam, 2005.
Overland, J. E. and Wang, M.: Future regional Arctic Sea ice declines, Geophys. Res. Lett., 34, L17705, doi:10.1029/2007GL030808, 2007.
PAME: Arctic Marine Shipping Assessment 2009 Report, Protection of the Arctic Marine Environment Working Group, Arctic Council, 2009.
Paxian, A., Eyring, V., Beer, W., Sausen, R., and Wright, C.: Present-Day and Future Global Bottum-Up Ship Emission Inventories Including Polar Routes, Environ. Sci. Technol., 44, 1333–1339, 2010.
Quinn, P. K., Bates, T. S., Baum, E., Doubleday, N., Fiore, A. M., Flanner, M., Fridlind, A., Garrett, T. J., Koch, D., Menon, S., Shindell, D., Stohl, A., and Warren, S. G.: Short-lived pollutants in the Arctic: their climate impact and possible mitigation strategies, Atmos. Chem. Phys., 8, 1723–1735, doi:10.5194/acp-8-1723-2008, 2008.
Rypdal, K., Rive, N., Berntsen, T., Klimont, Z., Mideksa, T., Myhre, G., and Skeie, R. B.: Costs and global impacts of black carbon abatement strategies, Tellus B, 61, 625–641, 2009.
Serreze, M. C., Holland, M. M., and Stroeve, J.: Perspectives on the Arctic's Shrinking Sea-Ice Cover, Science, 315, 1533–1536, doi:10.1126/science.1139426, 2007.
Shindell, D. and Faluvegi, G.: Climate response to regional radiative forcing during the twentieth century, Nat. Geosci., 2, 294–300, 2009.
Statistics Norway: Statbank: 03964 Emissions to air, by source and fuel (http://www.ssb.no/english/subjects/01/04/10/), last access: 26 March 2010, 2010.
Stroeve, J., Holland, M. M., Meier, W., Scambos, T., and Serreze, M.: Arctic sea ice decline: Faster than forecast, Geophys. Res. Lett., 34, L09501, doi:10.1029/2007GL029703, 2007.
UNECE: Protocol to the 1979 convention on Long-Range Transboundary Air Pollution to abate acidification, eutrophication and ground-level ozone, United Nations Economic Commission for Europe, 2005.
Wang, M. and Overland, J. E.: A sea ice free summer Arctic within 30 years?, Geophys. Res. Lett., 36, L07502, doi:10.1029/2009GL037820, 2009.
Wilson, K. J., Falkingham, J., Melling, H., and Abreu, R. D.: Shipping in the Canadian Arctic. Other possible climate change scenarios., IGARSS 2004: Proceedings of the IEEE International Geoscience and Remote Sensing Symposium, 2004.
Wood Mackenzie and Fugro Robertson: Future of the Arctic: A new dawn for exploration (Executive Summary), Wood Mackenzie and Fugro Robertson, 2006.

ACPD
11, 4913–4951, 2011

Table 1. The adopted emission factors per tonne oil equivalent extracted for 2004 (details in the Supplementary material). SO_2 and NO_x are based on the molecular weight and not the mass of S or N.

	CO_2 ($kg\,t^{-1}$)	CH_4 ($g\,t^{-1}$)	N_2O ($g\,t^{-1}$)	NMVOC ($g\,t^{-1}$)	SO_2 ($g\,t^{-1}$)	NO_x ($g\,t^{-1}$)	CO ($g\,t^{-1}$)	PM10 ($g\,t^{-1}$)	BC ($g\,t^{-1}$)	OC ($g\,t^{-1}$)
Norway	58	154	0.4	380	1	186	39	4	1.1	1.2
Russia East	69	620	0.5	128	186	121	31	50	15.7	17.0
Russia West	69	620	0.5	128	186	121	31	50	15.7	17.0
Canada	109	110	3.3	82	166	331	223	9	2.9	3.2
United States	389	1621	0.4	41	23	891	178	97	30.5	33.1
Greenland	58	154	0.4	380	1	186	39	4	1.1	1.2
Minimum	58	110	0.4	41	1	121	31	4	1	1

ACPD
11, 4913–4951, 2011
Future emissions in the Arctic
G. P. Peters et al.

Table 2. Estimated emissions from oil and gas extraction in the Arctic assuming 2004 emission factors in each year.

	Constant Emission Factors										
2004	Oil and gas (Mtoe)	CO_2 (Mt)	CH_4 (kt)	N_2O (t)	NMVOC (kt)	SO_2 (kt)	NO_x (kt)	CO (kt)	PM (kt)	BC (kt)	OC (kt)
Norway	45.7	2.6	7.0	19.2	17.4	0.1	8.5	1.8	0.2	0.1	0.1
Russia East	1.5	0.1	0.9	0.7	0.2	0.3	0.2	0.0	0.1	0.0	0.0
Russia West	812.8	55.8	504.0	383.9	103.7	151.4	98.7	25.2	40.6	12.8	13.8
Canada	1.8	0.2	0.2	5.9	0.1	0.3	0.6	0.4	0.0	0.0	0.0
United States	61.7	24.0	100.0	24.7	2.5	1.4	55.0	11.0	6.0	1.9	2.0
Greenland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum	923.5	82.8	612.1	434.4	123.9	153.4	163.0	38.4	46.9	14.7	16.0
2030	Oil and gas (Mtoe)	CO_2 (Mt)	CH_4 (kt)	N_2O (t)	NMVOC (kt)	SO_2 (kt)	NO_x (kt)	CO (kt)	PM (kt)	BC (kt)	OC (kt)
Norway	22.3	1.3	3.4	9.4	8.5	0.0	4.2	0.9	0.1	0.0	0.0
Russia East	15.4	1.1	9.6	7.3	2.0	2.9	1.9	0.5	0.8	0.2	0.3
Russia West	591.0	40.6	366.4	279.1	75.4	110.0	71.8	18.3	29.5	9.3	10.1
Canada	29.9	3.3	3.3	97.3	2.4	5.0	9.9	6.7	0.3	0.1	0.1
United States	107.1	41.7	173.6	42.8	4.3	2.4	95.5	19.1	10.4	3.3	3.5
Greenland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum	765.7	87.9	556.3	435.9	92.6	120.3	183.2	45.4	41.1	12.9	14.0
2050	Oil and gas (Mtoe)	CO_2 (Mt)	CH_4 (kt)	N_2O (t)	NMVOC (kt)	SO_2 (kt)	NO_x (kt)	CO (kt)	PM (kt)	BC (kt)	OC (kt)
Norway	56.1	3.2	8.7	23.6	21.3	0.1	10.5	2.2	0.2	0.1	0.1
Russia East	37.4	2.6	23.2	17.6	4.8	7.0	4.5	1.2	1.9	0.6	0.6
Russia West	572.5	39.3	355.0	270.4	73.0	106.6	69.5	17.7	28.6	9.0	9.7
Canada	58.4	6.4	6.4	189.9	4.8	9.7	19.3	13.0	0.5	0.2	0.2
United States	172.6	67.1	279.7	69.0	7.0	3.9	153.8	30.8	16.8	5.3	5.7
Greenland	17.2	1.0	2.6	7.2	6.5	0.0	3.2	0.7	0.1	0.0	0.0
Sum	914.1	119.6	675.5	577.8	117.4	127.3	260.9	65.5	48.1	15.1	16.4

ACPD
11, 4913–4951, 2011

Table 3. Estimated emissions from oil and gas extraction in the Arctic assuming 2004 Best Practice emission factors in each year.

	Best Practice										
2030	Oil and gas (Mtoe)	CO_2 (Mt)	CH_4 (kt)	N_2O (t)	NMVOC (kt)	SO_2 (kt)	NO_x (kt)	CO (kt)	PM (kt)	BC (kt)	OC (kt)
Norway	22.3	1.3	2.5	8.9	0.9	0.0	2.7	0.7	0.1	0.0	0.0
Russia East	15.4	0.9	1.7	6.2	0.6	0.0	1.9	0.5	0.1	0.0	0.0
Russia West	591.0	34.1	64.8	236.4	23.9	0.8	71.8	18.3	2.1	0.7	0.7
Canada	29.9	1.7	3.3	12.0	1.2	0.0	3.6	0.9	0.1	0.0	0.0
United States	107.1	6.2	11.8	42.8	4.3	0.1	13.0	3.3	0.4	0.1	0.1
Greenland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum	765.7	44.2	84.0	306.3	31.0	1.0	93.0	23.7	2.7	0.8	0.9
2050	Oil and gas (Mtoe)	CO_2 (Mt)	CH_4 (kt)	N_2O (t)	NMVOC (kt)	SO_2 (kt)	NO_x (kt)	CO (kt)	PM (kt)	BC (kt)	OC (kt)
Norway	56.1	3.2	6.2	22.5	2.3	0.1	6.8	1.7	0.2	0.1	0.1
Russia East	37.4	2.2	4.1	14.9	1.5	0.1	4.5	1.2	0.1	0.0	0.0
Russia West	572.5	33.1	62.8	229.0	23.2	0.8	69.5	17.7	2.0	0.6	0.7
Canada	58.4	3.4	6.4	23.4	2.4	0.1	7.1	1.8	0.2	0.1	0.1
United States	172.6	10.0	18.9	69.0	7.0	0.2	21.0	5.3	0.6	0.2	0.2
Greenland	17.2	1.0	1.9	6.9	0.7	0.0	2.1	0.5	0.1	0.0	0.0
Sum	914.1	52.8	100.3	365.7	37.0	1.3	111.0	28.3	3.2	1.0	1.1

ACPD
11, 4913–4951, 2011

Table 4. Base emission factors in kg emitted per tonne of fuel consumed for an internal combustion engine running on residual fuel oil, as well as emission reduction factors and corresponding emission factors for different pollutants for the years 2030 and 2050, based on the revised MARPOL 73/78 Annex VI effective as of 1 July 2010.

Pollutant	Base emission factor	Source	Reduction factor 2030	Reduction factor 2050	Emission factor [kg t^{-1}] 2030	Emission factor [kg t^{-1}] 2050
CO_2	3130	Buhaug et al. (2009)	0	0	3130	3130
CH_4	0.3	Buhaug et al. (2009)	0	0	0.3	0.3
N_2O	0.08	Buhaug et al. (2009)	0	0	0.08	0.08
NMVOC	2.4	Buhaug et al. (2009)	0	0	2.4	2.4
SO_x	54	Buhaug et al. (2009)	80%	80%	10.8	10.8
NO_x	78	Buhaug et al. (2009)	3.9%	3.3%	74.958	75.426
CO	7.4	Buhaug et al. (2009)	0	0	7.4	7.4
PM	5.3	Corbett et al. (2010)	20%	20%	4.24	4.24
BC	0.35	Corbett et al. (2010)	0	0	0.35	0.35
OC	1.07	Corbett et al. (2010)	20%	20%	0.856	0.856

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
ACPD
11, 4913–4951, 2011
Future emissions in the Arctic
G. P. Peters et al.

Table 5. Fuel consumption and emissions in gigagrams (kilotonnes) of various pollutants as a result of transpolar shipping and oil and gas-related shipping in the Arctic in 2030 and 2050.

Pollutant, short name	Emissions (kt)	
	2030	2050
Fuel consumption	2880	5180
CO_2	9010	16280
CH_4	0.87	1.6
N_2O	0.2	0.4
NMVOC	6.9	12.5
SO_x	31	55.9
NO_x	216.3	391
CO	21.3	38.4
PM	12.2	22.0
BC	1.0	1.8
OC	2.5	4.4

ACPD
11, 4913–4951, 2011

ACPD
11, 4913–4951, 2011

Future emissions in the Arctic

G. P. Peters et al.

Table 6. A comparison of the emissions from shipping and extraction of oil and gas. The shipping is split between transit, oil and gas, and other activities. The oil and gas covers actual emissions in 2004 and emission based on best practice in 2030 and 2050.

		Shipping									Oil and Gas		
		Transit			Oil and Gas			Other			2004 Actual, 2030/ 2050 Best Practice		
		2004	2030	2050	2004	2030	2050	2004	2030	2050	2004	2030	2050
Fuel consumption	kt	–	1190	1780	42	1690	3400	6671	6671	6671			
Carbon dioxide	CO_2 (Mt)	–	3.73	5.58	0.010	5.28	10.7	20.3	20.3	20.3	82.8	44.2	52.8
Methane	CH_4 (kt)	–	0.360	0.530	0.000	0.506	1.02	0.310	0.310	0.310	612	84.0	100
Nitrous oxide	N2O (t)	–	100	140	0.257	135	272	496	496	496	434	306	366
Non-methane volatile organic compounds	NMVOC (kt)	–	2.86	4.28	0.008	4.05	8.17	15.3	15.3	15.3	124	31.0	37.0
Sulphur oxides	SO_2 (kt)	–	12.8	19.2	0.170	18.2	36.7	281	56.3	56.3	153	1.05	1.25
Nitrogen oxides	NO_x (kt)	–	89.3	134	0.176	127	257	491	472	475	163	93.0	111
Carbon monoxide	CO (kt)	–	8.81	13.2	0.024	12.5	25.2	47.2	47.2	47.2	38.4	23.7	28.3
Particulate matter	PM (kt)	–	5.05	7.56	0.031	7.16	14.4	48.4	38.7	38.7	46.9	2.70	3.23
Black carbon	BC (kt)	–	0.420	0.620	0.001	0.590	1.19	1.15	1.15	1.15	14.7	0.85	1.01
Organic carbon	OC (kt)	–	1.02	1.53	0.002	1.44	2.91	3.87	3.10	3.10	16.0	0.92	1.10

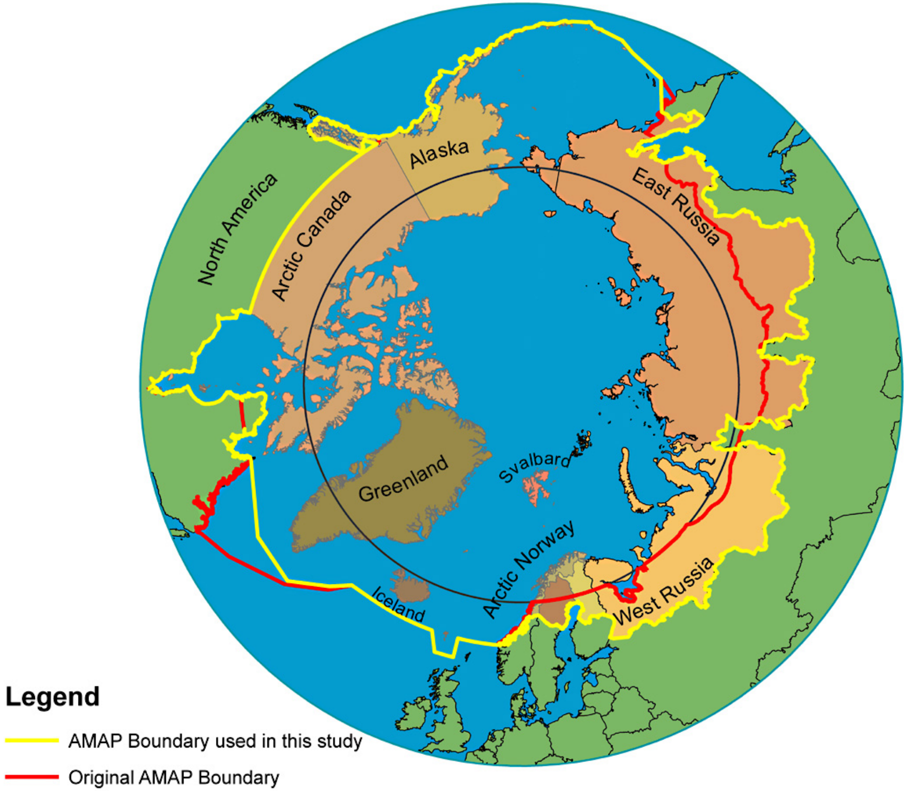

Fig. 1. The AMAP boundary used in this study compared to the official AMAP boundary. For the oil and gas production model (FRISBEE, see below), the AMAP area is further split into regions: Arctic Canada, Alaska, East and West Russia, Arctic Norway (not including Finland or Sweden), and Greenland.

ACPD
11, 4913–4951, 2011

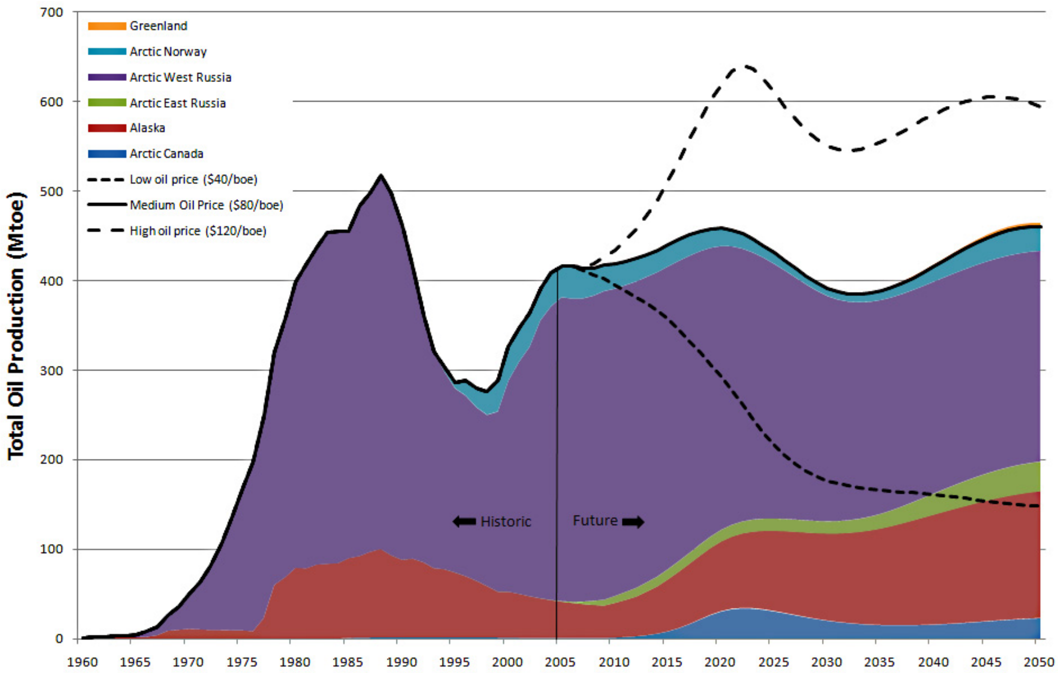

Fig. 2. Historic and estimated oil production in the Arctic with an oil price of $80/boe (by region) and compared to a low ($40/boe) and high ($120/boe) oil price.

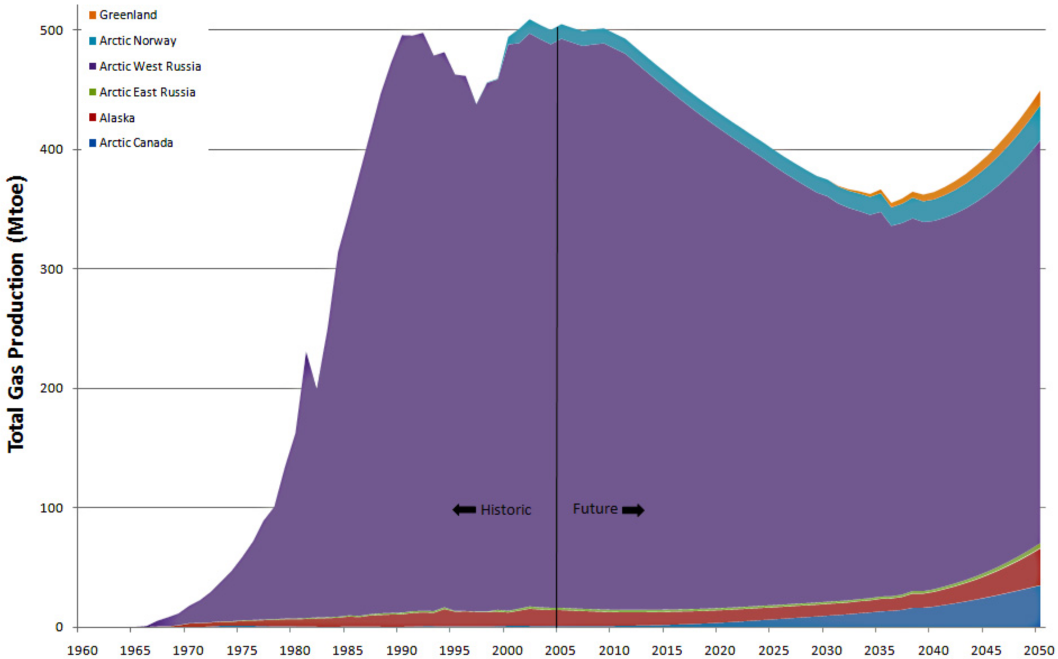

Fig. 3. Historic and estimated gas production in the Arctic.

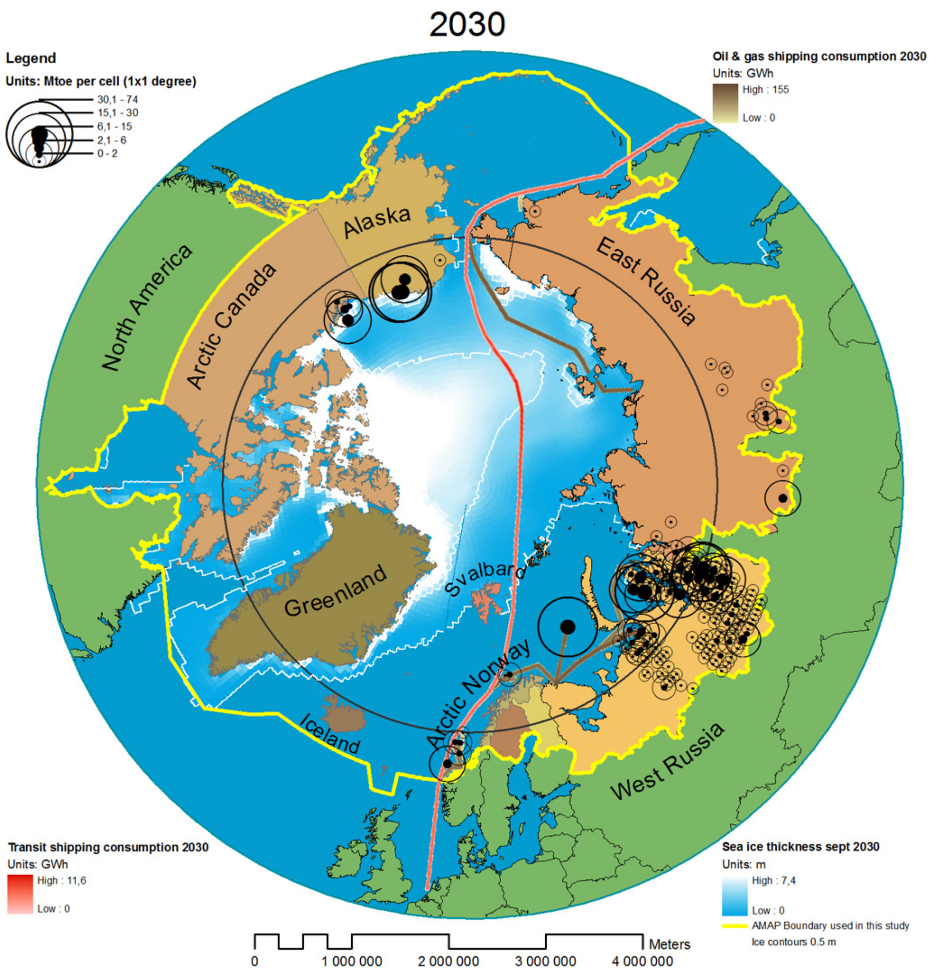

Fig. 4a.

ACPD
11, 4913–4951, 2011

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

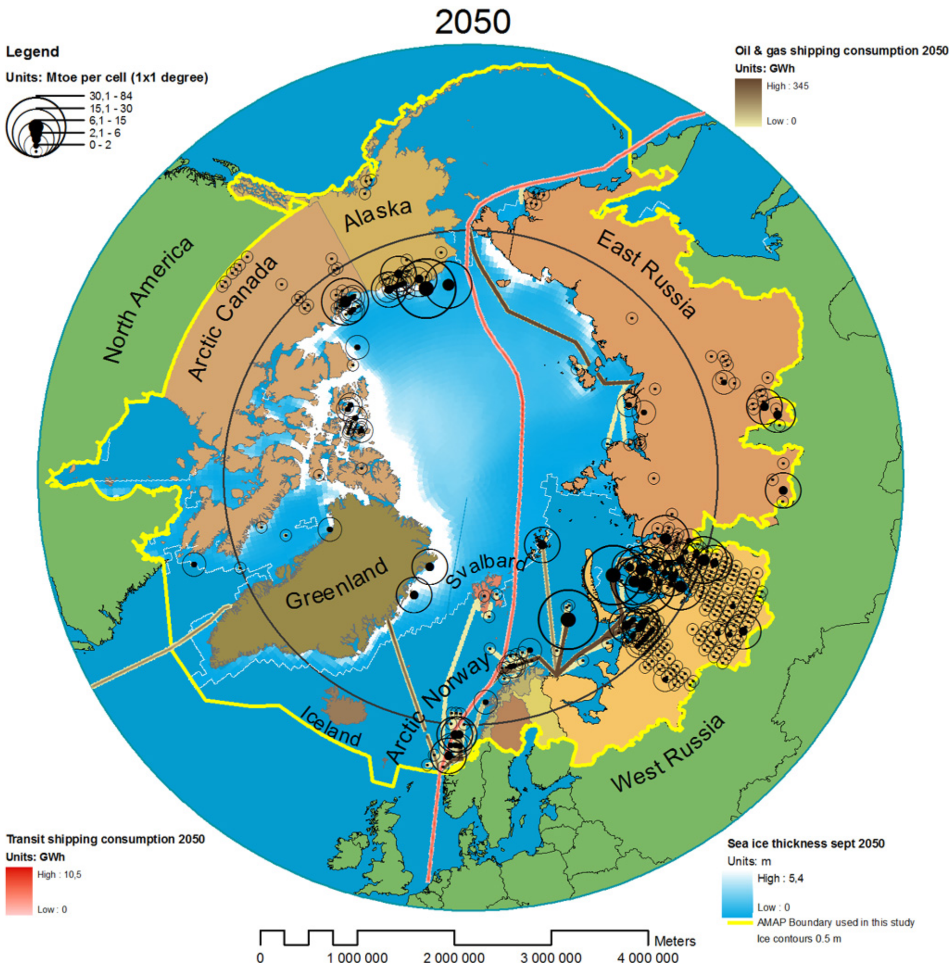

Fig. 4b.

ACPD
11, 4913–4951, 2011

Fig. 4. The oil and gas extraction (measured in Mtoe), energy consumption in transit and petroleum shipping (measured in GWh), and the September sea-ice extent in **(a)** 2030 and **(b)** 2050. These data are combined with emission factors to produce the results in respective tables. The transit shipping only occurs during the summer months, while the oil and gas transport occurs throughout the year.

ACPD
11, 4913–4951, 2011

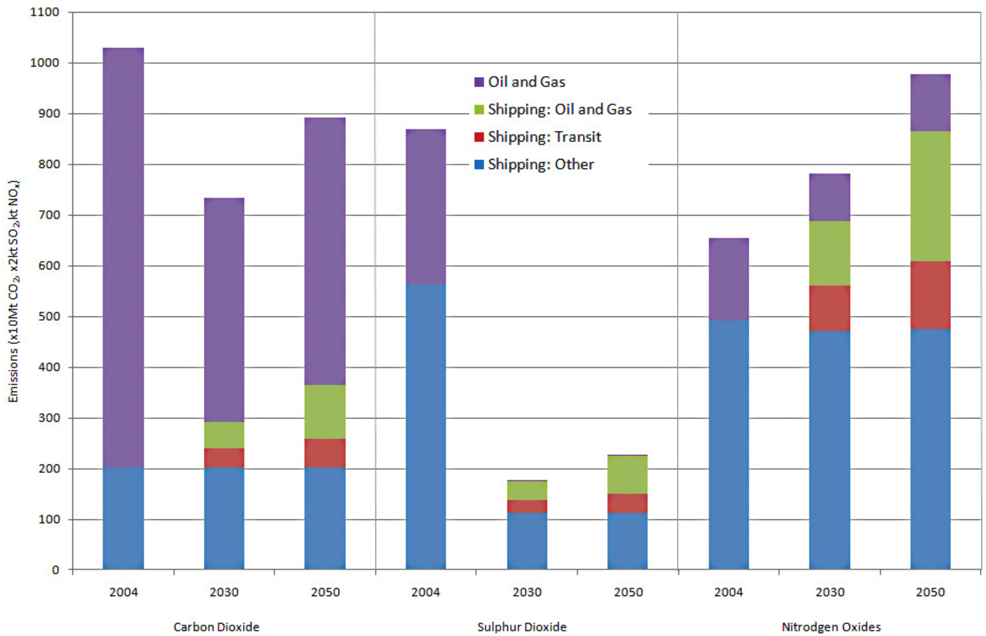

Fig. 5. A comparison of the different emission sources in the Arctic region for CO_2, SO_2, and NO_x (based on the data in Table 6). The "Other Shipping" is not based on calculations performed in the paper. Note the different scales: CO_2 is ×10 Mt CO_2, SO_2 is ×2 kt SO_2, and NO_x is kt NO_x.

ACPD
11, 4913–4951, 2011