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Short lived climate forcers from current shipping and petroleum activities in the Arctic

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Abstract

Atmospheric concentration changes and the resulting radiative forcing (RF) due to emissions from shipping and petroleum activity in the Arctic have been studied, using three-dimensional chemistry transport (OsloCTM2) and radiative transfer models. The present work focuses on short-lived climate forcers, based on a coherent dataset of present day emissions from petroleum and shipping activities in the Arctic region.

We find that the net forcing effect of Arctic shipping emissions of short-lived climate forcers (SLCFs) is negative, while the net effect from Arctic petroleum emissions of SLCFs is positive. The negative RF from Arctic shipping arises mainly from direct aerosol – and first indirect effects of sulphate. Positive RF from Arctic petroleum is mainly due to black carbon in air and deposited on snow and ice. Normalized forcing (RF per change in atmospheric burden) and global warming potentials (GWP) suggest that Arctic conditions (high solar angle, high surface albedo, summer season with midnight sun and polar night during winter) lead to different sensitivity to emissions here compared to lower latitudes.

1 Introduction

The Arctic is now experiencing some of the most rapid climate changes on earth. On average, temperature has risen approximately twice the rate of the rest of the world (ACIA, 2005). Repercussions of a warmer Arctic are melting glaciers, reduction in extent and thickness of sea ice, thawing permafrost and rising sea levels (Serreze et al., 2007). Warming also leads to an earlier onset of spring melt, lengthening the melting season. During the 2007 melt season, Arctic sea ice receded to the lowest level observed since satellite measurements began, leading to the first recorded complete opening of the Northwest Passage (NSIDC, 2007). This unlocking of the Arctic ocean will leave it increasingly open to human activity, particularly petroleum production and shipping. The response of the climate to these activities is not well studied.

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Petroleum and shipping activity emits a broad mix of gases and aerosols: long-lived greenhouse gases (GHGs), primary particles, such as organic- and black carbon (OC and BC), sulphur dioxide (SO_2), and the ozone (O_3) precursors nitrogen oxides (NO_x), carbon monoxide (CO) and nonmethanehydrocarbons (NMHCs). The emissions affects the chemistry and climate of the atmosphere through several mechanisms: by direct global warming from the GHGs, direct- and indirect effects from aerosols, and by formation of radiatively active O_3. Ozone also alters the oxidation capacity of the atmosphere, and will thereby also modify the lifetime of several compounds, including methane, contributing indirectly to radiative forcing (Quinn et al., 2008).

The Arctic is a region characterized by high solar angle, high surface albedo, low temperatures and long periods of darkness in the winter and sunlight in summer. These factors result in a different sensitivity to emissions compared to lower latitudes.

From previous studies, we know that climate impacts of emissions of some short-lived species are strongly dependent on their geographical location. For instance, Fuglestvedt et al. (1999) showed that NO_x emissions in South East Asia caused a radiative forcing up to 8 times higher than the same emission in Europe. Derwent et al. (2001), Wild et al. (2001) and Naik et al. (2005), modelled the indirect forcing (via O_3 and CH_4) from NO_x emissions and found large dependencies on the region where the emissions occur. Using several CTMs and GCMs, Berntsen et al. (2005) studied the effect of emission changes on concentrations, radiative forcing and temperature and found higher chemical and radiative sensitivity to emissions in Asia than for emissions in Europe, while forcing at higher latitudes were more effective in increasing global temperatures (i.e. higher climate sensitivity) due to feed-backs occurring at these high latitudes.

Berntsen et al. (2006) compared the effects of identical emission reductions in different regions and found large differences in the total forcing and temperature change, mainly due to the role of aerosols. Global and Arctic climate is highly sensitive to perturbations in Arctic concentrations of light absorbing particles like BC. BC leads to a decrease in surface albedo when deposited on snow and ice, and can contribute to

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a shift of the melting season to an earlier onset (Hansen and Nazarenko, 2004; Flanner et al., 2007). This will decrease the albedo in the Arctic, exposing a larger part of the Arctic surface for absorption of solar radiation. Due to the high sulphur content in marine fuels the impact of sulphur emissions from shipping on health and climate are potentially large (Corbett et al., 2007; Dalsøren et al., 2009; Eyring et al., 2010; Fuglestvedt et al., 2008, 2009). The indirect aerosol effect of sulphate is very dependent on geographical location (Lauer et al., 2007) this is also the case for the climate response of a given sulfate forcing (Shindell and Faluvegi, 2009).

Granier et al. (2006) studied future potential increases in shipping in the Arctic and found that the summer concentrations of surface ozone may be enhanced by a factor of 2–3, making the O_3 levels comparable to those seen in industrialized regions on the Northern Hemisphere.

Recently studies have presented more detailed ship emission inventories including polar routes (Paxian et al., 2010; Corbett et al., 2010; Peters et al., 2011), but few have investigated the effects from these emissions. Here, we use the inventories in Peters et al. (2011) to quantify the impact of current emissions from shipping and petroleum activity in the Arctic, in terms of concentration changes and radiative forcing. A global chemistry-transport model, OsloCTM2, and a radiative transfer model have been used.

2 Experimental method

2.1 Model description

OsloCTM2 is a global three-dimensional chemistry transport model for the troposphere and the lower stratosphere. Here, the OsloCTM2 model was run in T42 resolution ($2.8^\circ \times 2.8^\circ$) with 60 vertical layers using meteorological data from the IFS model (from ECMWF) for 2006. A tropospheric version of the model containing 85 chemical species was used. The applied chemistry scheme calculates the evolution of hydrogen, oxygen,

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nitrogen, and carbon containing gases and also sulphate, primary organic, nitrate and sea salt aerosols. See Myhre et al. (2009) for a description and evaluation of the aerosol module.

Modelled distributions of ozone and ozone precursors were evaluated and compared to observations for ship impacted air in previous studies (Endresen et al., 2003; Dalsøren et al., 2007, 2010). Based on comparisons Dalsøren et al. (2010) suggest increasing ship emissions as an important contributor to increasing background surface ozone in some coastal areas. The black carbon (BC) distribution in the model was compared to measurements and models in Koch et al. (2009). The study included a thorough discussion of model performance in the Arctic. Since then the model was updated with a more advanced BC scheme better reproducing BC measurements at high latitudes (Skeie et al., 2011; Lund and Berntsen, 2011). This scheme also includes uptake of BC on snow and ice covered surfaces.

For this study the model was run for 1 year, in addition to 3 months spin-up. Several runs are performed; basis simulations without emissions from Arctic ship and petroleum activity, and model runs with these emissions included. By comparing these runs, the contribution from the emissions was found.

2.2 RF calculations

The RF calculations are performed using a radiative transfer model (Myhre et al., 2009) developed from the DISORT code-base (Stamnes et al., 1988), with four short-wave radiation bands and eight streams. The temporal and spatial resolutions are the same as for OsloCTM2.

To calculate the total aerosol RF, we find the difference in top-of-atmosphere short-wave fluxes induced by adding all estimated emissions to a standard background aerosol distribution. We then remove single emission components and run separate calculations to find the individual component forcings. Black Carbon is considered as internally mixed. The scheme for calculating RFs from BC deposition on snow (Rypdal

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et al., 2009) is similar to that for the aerosol components. For O_3 changes the DISORT code is used for shortwave calculations and a broadband scheme is used for thermal infrared radiation (Myhre et al., 2011).

Calculation of the first indirect aerosol effect (cloud albedo effect) is performed through a parameterization of cloud droplet number concentration versus aerosol optical depth, following a method outlined in (Quaas et al., 2006; Quaas and Boucher, 2005). Using their terminology, we chose parameters of $a_0 = 4.3$, $a_1 = 0.3$, and constrain the droplet radii to lie between 2.0 and 25.0 µm. The indirect aerosol effect is only estimated for water clouds (no mixed phase or ice clouds), nor do we attempt to include other indirect aerosol effects.

2.3 Emission inventory

Arctic petroleum and global shipping emissions used in this study are developed by Peters et al. (2011). The gridded set of emissions consists of CO_2, CH_4 and N_2O, as well as NO_x, CO, NMVOC, BC, OC and SO_2 used as input. It is described in more detail in Peters et al. (2011). The emission volumes are given in Table 1. Non Arctic petroleum and global emissions from other sectors comes from the Edgar 3.2 inventory (Olivier et al., 2005). For natural emissions the RETRO data set (Schultz et al., 2007) is used.

From the start of Arctic oil and gas exploration in the 1950s, the production had a rapid growth until the fall of the Soviet Union in 1990. By mid-1990 the production had dropped to 80 % of peak levels. Now the production is back at 1990-levels (Peters et al., 2011). West Russia dominates Arctic petroleum production (83 % of cumulative production) followed by Alaska with 15 % (Peters et al., 2011). Around one-half of cumulative production is gas and the remainder oil and condensates.

Tourism, fishing and community re-supply dominate Arctic shipping (Peters et al. (2011) and references therein). Tourism mainly takes place along the coasts of northern Norway, Southwest Greenland and Svalbard. Fishing largely occurs on the ice-free water around Iceland and in the Bering, Barents and Norwegian Seas. Community

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re-supply is located along the Northern Sea Route (NSR) and the North West Passage. The bulk cargo is dominated by ship traffic along the coast of Norway and around Iceland, followed by export from a few large mining operations in Alaska and Russia. Oil and gas transported from the Arctic by ship is limited and for the most part located on the Eurasian side. The NSR was opened to foreign ships in 1991, and commercial transit traffic, except tourism, has taken place only along this route. 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 Uslan (Korea) and Rotterdam by 4000 nautical miles – 7400 km).

3 Results

The impact of emissions related to ship and petroleum activity in the Arctic was found by comparison between a basis simulation without these emissions in the Arctic and model runs where they were included. The AMAP definition was used to set borderlines for the Arctic region, for further description see Peters et al. (2011).

Tropospheric ozone is photochemically produced in the presence of nitrogen oxides ($NO_x = NO + NO_2$), carbon monoxide (CO) and hydrocarbons. In the pristine Arctic region where background concentrations of pollutants are low, the production rate of O_3 is limited by the amount of NO_x present. Figure 1 shows the NO_x increase in the lowest 1.5 km resulting from Arctic shipping and petroleum activity. The largest enhancement is spatially associated with the locations of oil and gas extraction sites, the largest ports in the Arctic area and in the vicinity of shipping lanes. In these areas Fig. 1 shows concentrations changes up to 0.6 mg m^{-2}.

Surface ozone change is shown in Fig. 2a and e, while Fig. 2b and f shows tropospheric ozone column in Dobson Units [DU], Fig. 2c and g zonal mean and Fig. 2d and h radiative forcing (top row ship and bottom row petroleum). Shipping produces the largest surface ozone enhancement with annual mean change up to 1.5 ppb situated along the Norwegian coast, and west coast of Greenland. During summertime values

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up to ~3 ppb (12 %) are found from shipping in these areas (not shown). Petroleum activity imposes an annual mean ozone change of 0.5 ppb in the vicinity of exploration sites in Alaska and West Russia. Close to the production location in Alaska, a slightly negative ozone change is found (Fig. 2e), due to ozone titration in wintertime. During winter a negative concentration change of about 2 ppb arises, while in summertime the change is +1 ppb (5 %). Wintertime titration occurs when NO reacts with O_3 to produce NO_2 and O_2, but NO_2 is not reformed to NO and O because of photochemical inactivity. Shipping contributes to an enhancement of 0.2 DU (tropospheric O_3 column), whereas the concentration change is up to 0.1 DU from petroleum activity. Seasonal zonal means are given in Fig. 3. The O_3 perturbation is largest during summer, for both emission sectors, due to active photochemistry.

The annual direct radiative forcing of O_3 from shipping is 4.19 W m^{-2} in the band 60–90° N and from oil and gas 1.28 m W m^{-2}, see Table 2. The difference in forcing is related to the difference in NO_x emissions from the two sources (shipping about 3 times larger than oil/gas, Table 1). However, ozone chemistry is non-linear and the difference in the resulting radiative forcing is not equal to the difference in emission of O_3 precursors. Figure 7 shows global annual mean RF.

The ship emissions of methane in this study (Table 1) are negligible compared to the total global methane emissions from all anthropogenic and natural sources. The current methane emissions from Arctic oil and gas activity (Table 1) are also small in such a context (approximately 1 per mille of total global source). We therefore expect the radiative forcing due to direct methane emissions to be small. But by changing OH, methane's most important reaction species in the atmosphere, emissions of short-lived components (CO, NO_x and NMVOCs) influence the chemical loss of methane. Based on methane lifetime calculations with OsloCTM2 we used the approach described in Berntsen et al. (2005); Myhre et al. (2011) to calculate the resulting global radiative forcing. Due to the relatively high NO_x/CO emission ratio both the Arctic shipping and petroleum activity leads to increases in OH and thereby decreases in methane lifetime. However, the changes in OH are rather small due to inactive photochemistry

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in periods of polar darkness. The effect on methane loss is further limited by low temperatures prevailing for most of the year in the Arctic. Due to this it is mainly the ship emissions that have a significant impact on methane lifetime since the traffic and effect on ozone (Fig. 3) peak during summer. We find the methane RF from shipping to be $-0.59\,\mathrm{m\,W\,m^{-2}}$ (global mean). This further results in a methane-induced ozone RF of $-0.22\,\mathrm{m\,W\,m^{-2}}$ and stratospheric water vapour RF of $-0.09\,\mathrm{m\,W\,m^{-2}}$. For the petroleum activity the forcings are very small amounting to $-0.03\,\mathrm{m\,W\,m^{-2}}$ for methane, $-0.01\,\mathrm{m\,W\,m^{-2}}$ for ozone and $-0.005\,\mathrm{m\,W\,m^{-2}}$ for stratospheric H_2O.

The impacts to tropospheric column of black carbon from Arctic shipping and petroleum are shown in Fig. 4a and b. Because of the lifetime of BC, which is on the order of days, the perturbations occur near emission locations, for shipping along the coast of Norway, west coast of Greenland and along the Alaska Peninsula, and petroleum in west Russia and east Alaska. Column changes in BC have a much larger amplitude from petroleum than shipping, with an annual mean burden of $4.1\,\mathrm{\mu g\,m^{-2}}$ (60–90° N) compared to $0.38\,\mathrm{\mu g\,m^{-2}}$ due to shipping (Table 2). The emissions from petroleum are confined over a few permanent extraction sites, while emissions from shipping are distributed over a larger area. The higher BC emissions from petroleum and the limited emission area, leads to a higher black carbon concentration, and a high maximum value ($\sim 80\,\mathrm{\mu g\,m^{-2}}$). Radiative forcing from petroleum emissions in the Arctic is also higher (about 10 times) than from shipping, $6.5\,\mathrm{m\,W\,m^{-2}}$ and $0.60\,\mathrm{m\,W\,m^{-2}}$ (60–90° N), respectively. The global mean RF found here for BC in air from shipping is 5 % of total shipping RF found in Balkanski et al. (2010) ($1.6\,\mathrm{m\,W\,m^{-2}}$; internal mixture). Organic carbon RF yields 2 % of the total shipping value.

Black carbon deposited on snow and ice alters the albedo, which accelerates the melting process in spring (Flanner et al., 2007), and can warm the surface. The radiative forcing from BC on snow is $20.2\,\mathrm{m\,W\,m^{-2}}$ for petroleum activity, and $0.47\,\mathrm{m\,W\,m^{-2}}$ due to shipping (Fig. 4c and d). The large difference stems from different sizes in emission volumes, but also in the fact that shipping occur mainly during months where snow and ice-extension is at it lowest, while emissions from petroleum occur throughout the

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year. There is no sunlight in winter, and thus no effect on radiative forcing from black carbon on snow, but it accumulates in the snow over the winter. In spring when the snow starts to melt, it reappears and absorbs sunlight, which affects the radiative budget and may accelerate the melting process.

For concentration changes in organic carbon (OC), the spatial extent is similar to black carbon (not shown here). However the two carbonaceous compounds have different optical properties. Whereas BC is an absorbing aerosol, OC scatters sunlight. The OC values are however weak. $-0.13\,\mathrm{m\,W\,m^{-2}}$ from shipping and $-0.42\,\mathrm{m\,W\,m^{-2}}$ (60–90° N) from petroleum. The small values are results of the fact that the effect on the radiative balance from reflective aerosols over bright surfaces is small.

Shipping contributes a much higher share of the Arctic SO_2 emissions than petroleum activity. This is shown in Fig. 5, which show concentration changes in SO_4. SO_4 is formed by the oxidation of SO_2 and is the dominant aerosol component from shipping emissions. It is also one of the most important contributors to radiative forcing from shipping, together with the indirect effect to which sulphur contributes greatly (Figs. 6 and 7). SO_4 direct aerosol effect have a negative forcing because it reflects incoming solar radiation. The radiative forcing from shipping in the Arctic is $-5.78\,\mathrm{m\,W\,m^{-2}}$ (60–90° N) and the first indirect aerosol effect $-18.8\,\mathrm{m\,W\,m^{-2}}$, see Table 2. The first indirect aerosol effect is shown in Fig. 6. SO_2 emissions from shipping are high because of high average sulphur content in marine heavy fuels used by most ocean-going ships (Endresen et al., 2005). Balkanski et al. (2010) found the direct radiative forcing for SO_4 from total shipping to be $-26.3\,\mathrm{m\,W\,m^{-2}}$, which makes the Arctic shipping contribution found here (global mean) 1.7 % of total shipping.

The Arctic emission of SO_2 from petroleum extraction (Table 1) results in radiative forcing from SO_4 direct aerosol effect of $-1.9\,\mathrm{m\,W\,m^{-2}}$ (60–90° N) (Table 2), and the indirect aerosol effect is $-2.0\,\mathrm{m\,W\,m^{-2}}$.

Effects on nitrate are calculated, but are negligible in magnitude (shipping global mean RF 0.26 % of total anthropogenic RF found in Myhre et al. (2009), and petroleum RF global mean 0.013‰ of total anthropogenic RF).

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The indirect aerosol effect dominates shipping contribution, while for petroleum, the effect of BC on snow is dominating, followed by BC in air. Thus, due to short-lived climate forcers, shipping emissions exert a net negative radiative forcing while the net effect from petroleum is positive.

4 Discussion

The difference in sizes of emitted volume for the components results in, in terms of forcing, different responses. Shipping has larger NO_x and SO_2 emissions, while petroleum has larger emissions of black carbon. Negative RF from sulphate dominates the response from shipping. Positive RF from black carbon, both in air through the direct aerosol effect and deposited on snow, gives the largest effect from petroleum emission. This is clear from Fig. 7 and Table 2. Effects from short-lived climate forcers are dependent on the chemical, physical and meteorological conditions in the emission region. Due to the large snow covered areas in the Arctic, deposition of black carbon on snow and ice surfaces is more likely in this area, and can thus have a greater effect here compared to at lower latitudes. The effect of BC on snow from petroleum is as large as $20.2\,\mathrm{m\,W\,m^{-2}}$.

Radiative forcing per mass unit, i.e. normalized forcing (NRF) reveal the most "efficient" component when it comes to radiative forcing. Normalized forcing with respect to change in atmospheric burden is shown in Table 3. The models used in Myhre et al. (2011) found O_3 NRF from shipping to be $30\,\mathrm{m\,W\,m^{-2}\,DU^{-1}}$ (range from 29 to 32). The global mean found here is not as high, $22\,\mathrm{m\,W\,m^{-2}\,DU^{-1}}$, while a mean in the band 60–90° N is a $34\,\mathrm{m\,W\,m^{-2}\,DU^{-1}}$. For emissions from petroleum these values are 27 and $28\,\mathrm{m\,W\,m^{-2}\,DU^{-1}}$. Berntsen et al. (2006)'s work on comparing the potential climate effects of mitigation measures applied to various regions found O_3 NRFs to be 35, 40, 38, $37\,\mathrm{m\,W\,m^{-2}\,DU^{-1}}$ for Europe, China, South Asia and South America, respectively.

Berntsen et al. (2006) found sulphate NRFs for Europe, China, South Asia and South America to be −213, −186, −224 and $-268\,\mathrm{W\,g^{-1}}$. Sulphate from Arctic shipping is

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somewhat stronger than for all of these regions (−320 (global) and −292 (60–0° N), see Table 3), while petroleum global (−232) is stronger than all the regions except South America. Petroleum 60–90° N (−207) is weaker than all the regions. Compared with numbers for total antrophogenic emissions of sulphate in Myhre et al. (2009), the normalized RF for Arctic shipping emissions are somewhat stronger. Myhre et al. (2009) found $-227\,\mathrm{Wg}^{-1}$. The reason for stronger NRF for shipping in Arctic is due to the higher water uptake since relative humidity is high. Sulphate from petroleum are closer to the Myhre et al. (2009) value.

NRFs for black carbon found here (Table 3) are comparable with $1693\,\mathrm{Wg}^{-1}$ found in Myhre et al. (2009). Here, global means of 1630 and $1790\,\mathrm{Wg}^{-1}$ are found from Arctic shipping and petroleum, respectively. BC in the Arctic has a longer lifetime than at lower latitudes, which gives a stronger effect, but because the concentration changes due to shipping and petroleum activities are low in the atmosphere, the resulting values are comparable to BC at other regions.

OC NRFs are weaker here with −118 (shipping) and −121 (petroleum) compared to −273 in Myhre et al. (2009) and −152, −122, −136, −131 in Berntsen et al. (2006). Nitrate NRFs are comparable for shipping; $-208\,\mathrm{Wg}^{-1}$ (Myhre et al., 2009) and $-206\,\mathrm{Wg}^{-1}$ (global mean) here, while petroleum is weaker, with a value of $-102\,\mathrm{Wg}^{-1}$. The weaker values found here are because reflective aerosols over bright surfaces, as in the Arctic, results in small radiative forcings compared to over darker surfaces.

Based on the concept of Radiative Forcing, the Intergovernmental Panel on Climate Change has employed the metric GWP (Global Warming Potential) as a tool to quantify and compare the potential impact of different climate change agents (Forster et al., 2007). GWP is a metric defined as the integrated RF caused by a pulse emission of 1 kg of a trace gas, over a chosen time horizon, relative to the RF of 1 kg of the reference gas CO_2:

$$\mathrm{GWP}(H)_t = \frac{\int_0^H RF_i(t)dt}{\int_0^H RF_{\mathrm{CO}_2}(t)dt} \quad (1)$$

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where H is the chosen time frame. Table 4 gives GWP for BC, OC, SO_4 and indirect aerosol effects from shipping and petroleum on time frames of 20, 100 and 500 years. GWPs for BC in air are comparable for shipping and petroleum, while for BC on snow the GWPs are about 4 times stronger for petroleum than shipping. Also, for sulphate the two sectors are comparable, while for the indirect aerosol effect the GWPs are much stronger (about 6 times) for shipping than for petroleum. GWPs for OC are comparable for shipping and petroleum.

The GWPs found here for BC in air are somewhat stronger than the GWPs in Fuglestvedt et al. (2010), who found 1600, 460 and 140 for $H = 20$, $H = 100$ and $H = 500$, respectively. Values for BC GWP found in Bond et al. (2011) are 2600 ± 1300 and 740 ± 370 for time horizons of 20 and 100 years, which are comparable to our numbers.

The OC values are comparable to Fuglestvedt et al. (2010) ($H = 20 : -240, H = 100 : -69, H = 500 : -21$). Sulphate values are about 2 times stronger in Fuglestvedt et al. (2010) (−140, −40, −12, for the same time horizons) than here, due to the prevailing Arctic conditions.

4.1 Uncertainties

The uncertainties in emissions are discussed in detail by Peters et al. (2011). Both the OsloCTM2 model and the RF model used in this study participated in studies for the IPCC AR 4 report. For accumulated uncertainty in RF we expect similar levels per component as reported in the IPCC studies (Forster et al., 2007) both regarding the range of value uncertainties and confidence level of structural uncertainties. As mentioned earlier, specific conditions in the Arctic may however make uncertainties higher for certain processes and components. In this study, the ship emissions are instantaneously dispersed over the model grid box. Studies (Huszar et al., 2010; Paoli et al., 2011; Song et al., 2003; von Glasow et al., 2003; Chen et al., 2005; Kasibhatla et al., 2000; Franke et al., 2008) have shown that neglecting plume-effects, i.e. not accounting for the expansion phase of a ship plume, might lead to an overestimation

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of the ozone production. Chen et al. (2005) finds underestimations of in-plume NO_x loss rate to be about 30%. Huszar et al. (2010) suggests the overestimation of O_3 to be 10–30 %.

5 Conclusions

The emissions from shipping and petroleum activity in the Arctic have an effect on concentration levels of several atmospheric components. These gases and aerosols leads directly and indirectly to radiative forcing in the Arctic region. For shipping the strongest effects, in terms of RF, are sulphur direct effect and first indirect aerosol effect. For petroleum black carbon on snow exert the largest radiative forcing, followed by black carbon in air. Ozone effects, i.e concentration changes and radiative forcing, are strongest for shipping emissions compared to petroleum emissions.

We find that the net forcing effect of Arctic shipping emissions of short-lived climate forcers (SLCFs) is negative, while the net effect from Arctic petroleum emissions of SLCFs is positive. The negative RF from Arctic shipping arises mainly from direct aerosol – and first indirect effects of sulphate. Positive RF from Arctic petroleum is mainly due to black carbon in air and deposited on snow and ice.

Normalized forcing (RF per change in atmospheric burden) and global warming potentials (GWP) suggest that Arctic conditions (high solar angle, high surface albedo, summer season with midnight sun and polar night during winter) lead to different sensitivity to emissions here compared to lower latitudes.

NRF for BC in air found here is comparable to other studies. The NRF for OC show that the effect in the Arctic is not as strong as in other regions. The O_3 NRFs found here are comparable to other studies. NRF for sulphate from Arctic shipping is stronger than NRF in other regions.

GWPs for BC in air do not differ much between shipping and petroleum, but are somewhat larger than other studies. BC in snow, however, are stronger for petroleum activities compared to shipping. GWP for the indirect aerosol effect for shipping

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activities is stronger than for petroleum. For sulphate the GWP are comparable between the two sectors, but stronger than what is found by Fuglestvedt et al. (2010).

Thus, when regarding the short-lived components from shipping and petroleum, as done here, the sensitivity in the Arctic seems to be different than at other latitudes.

The melting of Arctic sea ice will unlock the Arctic ocean area, leaving it increasingly open to human activity. Particularly shipping and petroleum production are expected to change. Here we have investigated the effects of current shipping- and petroleum emissions. Future emissions could potentially have a significant effect on Arctic environment, regional air pollution levels and radiative budget. This will be addressed in upcoming studies.

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Table 1. Emission volumes, shipping and petroleum activity in 2004 (values from Peters et al., 2011).

Component	Shipping 2004	Petroleum 2004
NMVOC (kt)	15.3	124
SO_2 (kt)	281.2	153
NO_X (kt)	491.2	163
CO (kt)	47.2	38.4
PM (kt)	48.4	46.9
BC (kt)	1.15	14.7
OC (kt)	3.87	16.0
CO_2 (Mt)	20.3	82.8
CH_4 (kt)	0.31	612
N_2O (t)	496.3	434

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Table 2. Global annual mean burden ($\mu g\,m^{-2}$) (For O_3: (DU)) and radiative forcing ($m\,W\,m^{-2}$) from ship and petroleum activity in 2004.

	Burden ($\mu g\,m^{-2}$)				Radiative Forcing ($m\,W\,m^{-2}$)			
	Shipping		Petroleum		Shipping		Petroleum	
Component	Global	60–90°	Global	60–90°	Global	60–90°	Global	60–90°
Sulphate	1.41	19.9	1.0	9.2	−0.45	−5.78	−0.24	−1.9
Nitrate	0.30	0.75	0.003	−0.024	−0.06	−0.13	−0.0003	0.0033
BC air	0.04	0.38	0.48	4.1	0.08	0.60	0.86	6.5
BC snow					0.03	0.47	1.49	20.2
OC	0.17	1.37	0.49	4.63	−0.02	−0.13	−0.06	−0.42
Indirect					−1.97	−18.8	−0.18	−2.0
Ozone	0.026	0.12	0.008	0.046	0.57	4.19	0.23	1.28
Methane					−0.59		−0.03	
CH_4 induced O_3					−0.22		−0.01	
Strat. water vapour					−0.09		−0.005	

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Table 3. Global and 60–90° N Radiative Forcing normalized to annual, global and 60–90° N, change in atmospheric burden (Wg^{-1}) and ($m\,W\,m^{-2}\,DU^{-1}$) for O_3 from ship and petroleum activity in 2004.

	Normalized RF (Wg^{-1})			
	Shipping		Petroleum	
Component	Global	60–90°	Global	60–90°
Sulphate	−320	−292	−232	−207
Nitrate	−206	−168	−102	−132
BC air	1630	1600	1790	1580
OC	−118	−94	−121	−90
Ozone ($m\,W\,m^{-2}\,DU$)	22	34	27	28

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Table 4. GWP values for shipping and petroleum emissions (global mean) for 20, 100 and 500 year time horizons. Sulphate are calculated on SO_2 basis (not S-basis).

	GWP					
	Shipping			Petroleum		
Component	$H = 20$	$H = 100$	$H = 500$	$H = 20$	$H = 100$	$H = 500$
Sulphate	−65	−18	−6	−64	−18	−5
Indirect*	−283	−80	−24	−48	−14	−4
BC air	2816	801	243	2369	673	205
BC snow	1056	300	91	4104	1166	354
OC	−209	−59	−18	−152	−43	−13

* The GWP calculations for indirect aerosol effect are attributed to SO_2 emissions. Note that the indirect aerosol effect is calculated including all the aerosols, but sulphate is the dominating contributer.

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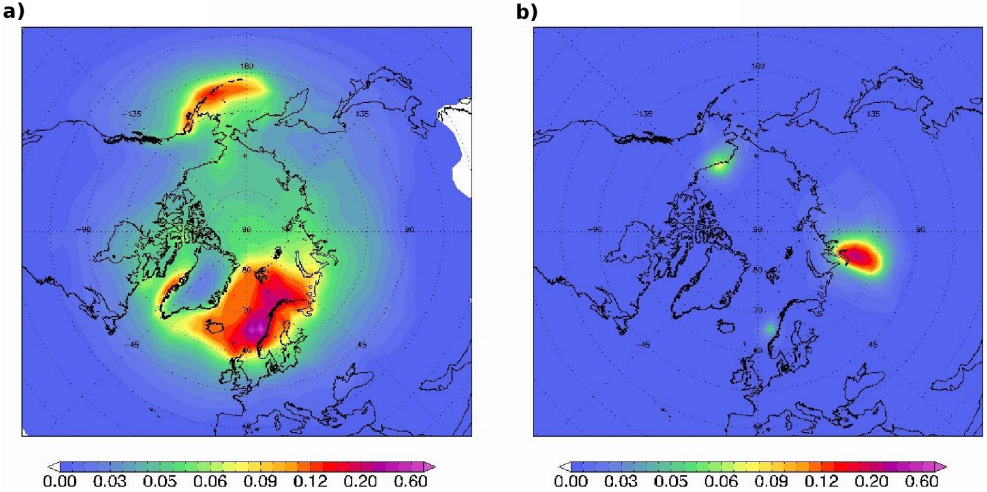

Fig. 1. Yearly average contribution to NO_x ($mg\,m^{-2}$) in the lowest 1.5 km of the troposphere from **(a)** shipping activity and **(b)** petroleum activity in 2004.

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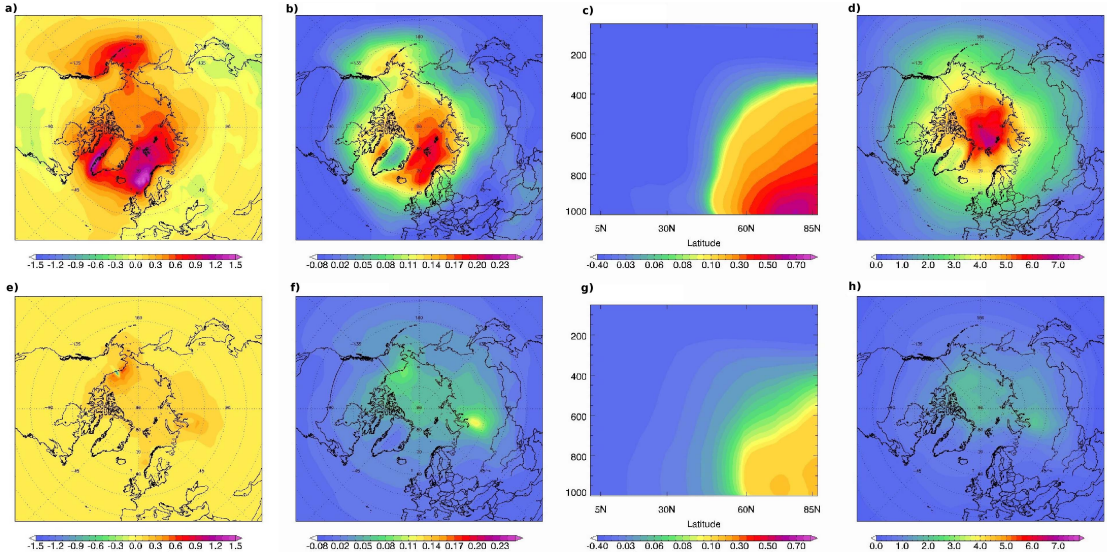

Fig. 2. O_3 effects from Arctic shipping and petroleum emissions. Top panel **(a)**, **(b)**, **(c)** and **(d)** are responses from shipping activity, while lower panel **(e)**, **(f)**, **(g)** and **(h)** are responses from petroleum (all for 2004). (a) and (e) Annual mean contribution to surface O_3 (ppb). (b) and (f) Annual mean impact on tropospheric O_3 column (DU). (c) and (g) Annual zonal mean O_3 (ppb). (d) and (h) Radiative forcing (m W m^{-2}) due to the ozone changes.

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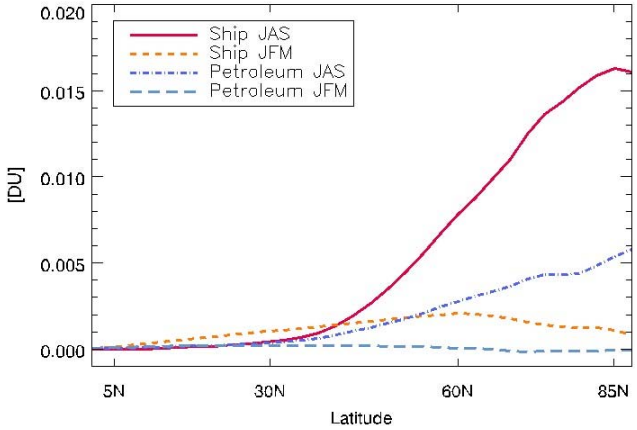

Fig. 3. Zonal mean ozone due to shipping and petroleum activity in summer and winter 2004. (JFM = January, February, March. JAS = July, August, September).

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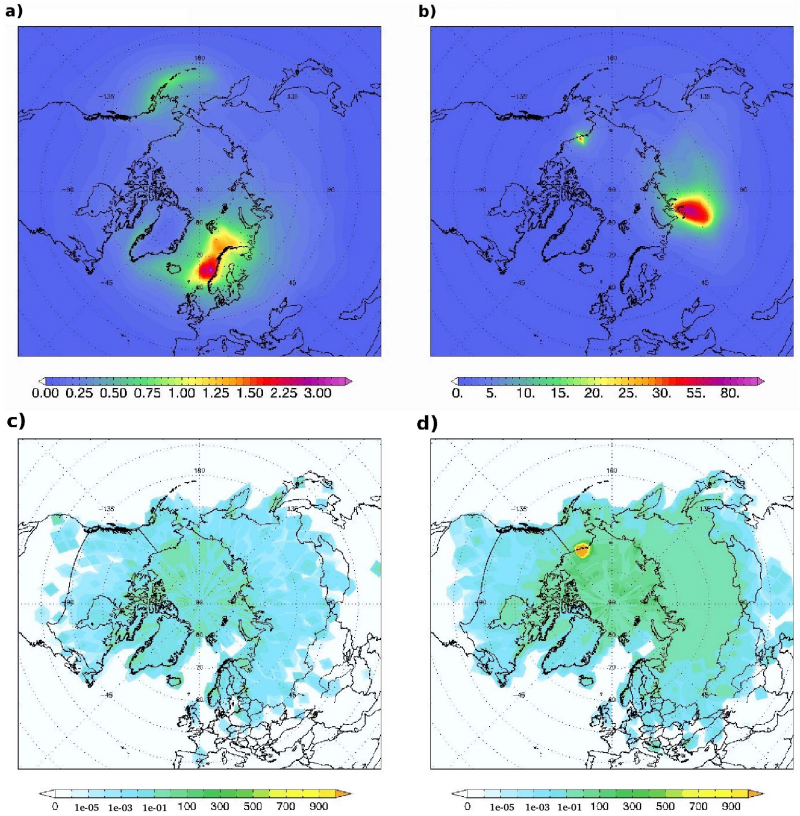

Fig. 4. BC effects from Arctic shipping and petroleum emissions. **(a)** Contribution to tropospheric column of black carbon ($\mu g\,m^{-2}$) from Arctic shipping activity in 2004. **(b)** Contribution to tropospheric column of black carbon ($\mu g\,m^{-2}$) from Arctic petroleum activity in 2004. **(c)** Radiative Forcing from black carbon on snow ($m\,W\,m^{-2}$) from Arctic shipping activity in 2004. **(d)** Radiative Forcing from black carbon on snow ($m\,W\,m^{-2}$) from Arctic petroleum activity in 2004.

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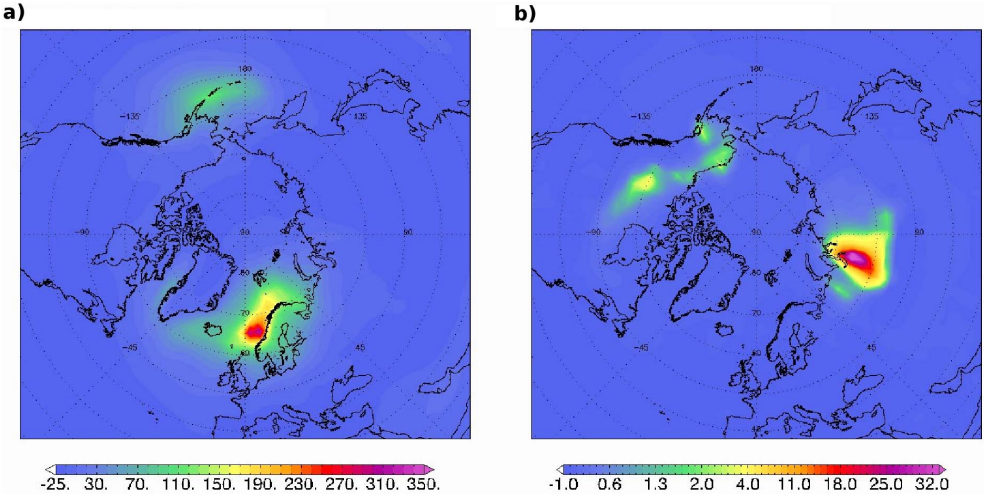

Fig. 5. Contribution to tropospheric column of sulphate ($\mu g\,m^{-2}$) from **(a)** shipping and **(b)** petroleum activity in 2004.

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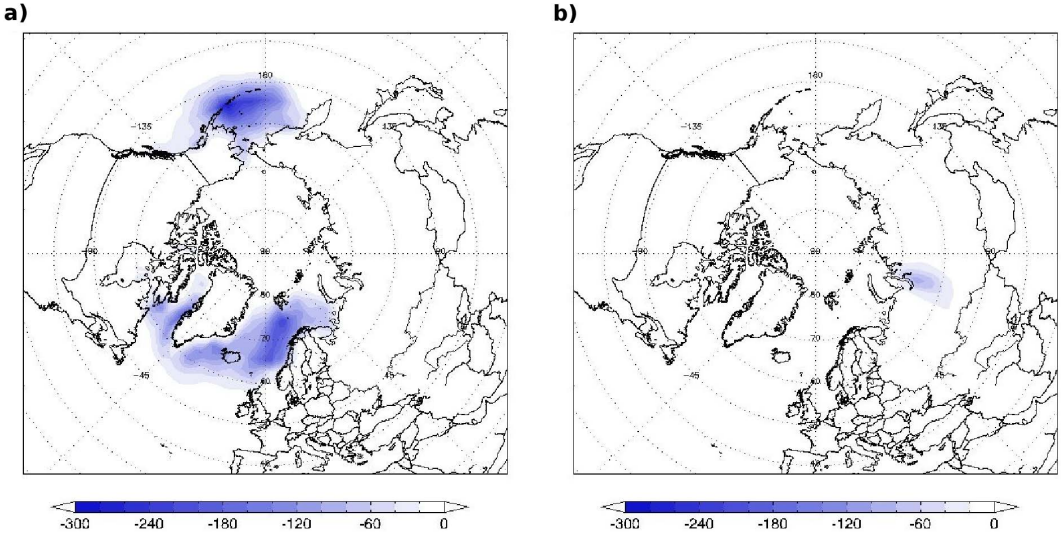

Fig. 6. Indirect radiative forcing (m W m^{-2}) from **(a)** shipping and **(b)** petroleum activity in 2004.

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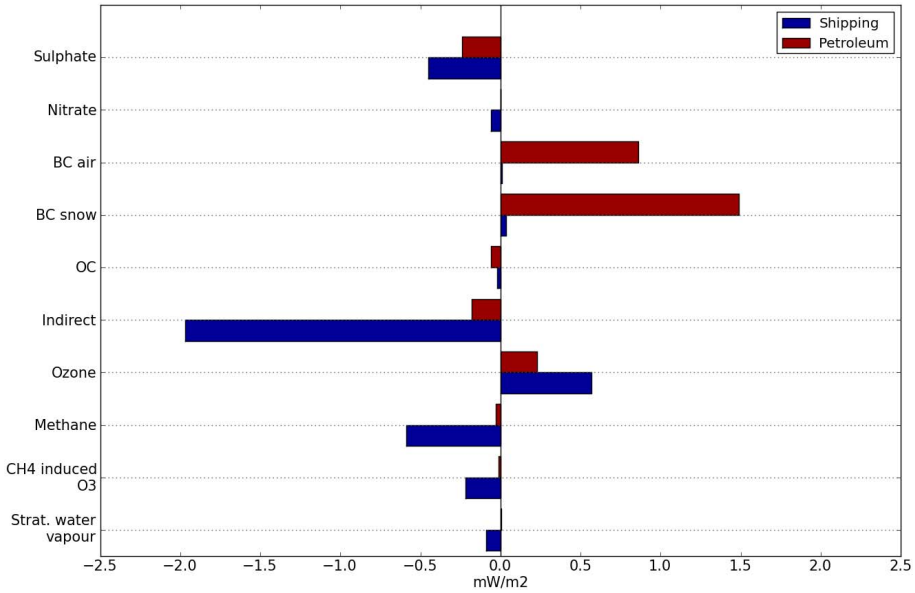

Fig. 7. Global and annual radiative forcing (m W m^{-2}) for the different short lived components from shipping and petroleum emissions.

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