UiT THE ARCTIC UNIVERSITY OF NORWAY

Faculty of Bioscience, Fisheries and Economics
Department of Arctic and Marine Biology

# Navigare necesse est

*Bio - Environmental implications of shipping in the European Arctic*

**Lars-Henrik Larsen**

*A dissertation for the degree of Philosophiae Doctor – January 2017*

The title of the thesis is the command ("navigare necesse est" – "we have to sail") given by the Roman General Pompeius in 56 BC, when his fleet of galleys were laying idle on the shores of Northern Africa, loaded with grain and foodstuff, awaiting the passage of a storm to be able to return to Rome.

*That was the period when the environment posed a threat to vessels and seafarers; and nobody had given the opposite condition a thought; that navigation in some distant future would cause environmental impacts and in some cases poses a threat to nature – a scene change brought about in the 1960 - 70's.*

Front page photo:
Rv. Helmer Hanssen from UiT, The Arctic University of Norway in Ny Ålesund harbour (78° 55' 30''N, 11° 55' 20''E) at noon on 20 January 2014. Photo: Malin Daase, UiT.

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# Acknowledgements

This PhD study is carried out at the department of Arctic and Marine Biology at UiT the Arctic University of Norway and Akvaplan-niva. The thesis is part of a cross-disciplinary research initiative entitled A-lex, led by the Faculty of Law at UiT, and carried out in cooperation with Marintek, Akvaplan-niva and the Faculty of Humanities, Social Sciences and Education at UiT. A-lex is funded by the Fram Centre Research flagship "Sea Ice in the Arctic Ocean, Technology and Systems of Agreements", the Barents 2020 program of the Norwegian Ministry of Foreign Affairs, and the Research Council of Norway.

The A-lex project was initiated by professor Tore Henriksen, UiT, who is gratefully acknowledged for leading the development of the application to the Ministry of Foreign Affairs, in true belief of the value of cross-disciplinary research.

Akvaplan-niva is partner in A-lex, and my PhD project has been carried out within the company's project portfolio, and in parallel with my work as manager of the company's Marine Environmental Department. I am extremely grateful to my colleagues at Akvaplan-niva, particularly those of you whom I have had the pleasure of implementing the project in cooperation with. Kjetil Sagerup, principal discussion- and project implementation partner – you have taught me a lot about theoretical and practical science. Chris Emblow, your skills in GIS and English language has contributed significantly to layout, design of maps and manuscripts quality. Rune Rautio, Rune Palerud, Alexei Bambulyak, Salve Dahle, Anita Evenset and Hector Andrade are acknowledged for valuable input to the project during its various phases.

My thesis has been supervised by Professor Stig Falk-Petersen and Professor Torstein Pedersen UiT, who are greatly acknowledged for providing skilled advice, comments and "adjustments of the set course" during the travel.

My fellow authors of the research publications are also greatly acknowledged.

Photos often say more than a thousand words; The following photographers are acknowledged for letting me include their photos in the dissertation: Malin Daase, Kjetil Sagerup, Maritime New Zealand, Salve Dahle, Bjørn Gulliksen, Christian Lydersen, Cathrine Stephansen, Rune Palerud, Michael Carroll, Anita Evenset and Guttorm Christensen.

This PhD project was implemented during a time of my life when all the parental duties of being a family dad (parent's meetings, school class trips and excursions, soccer coaching, transportation to horseback riding, swimming, musical rehearsing and car driving practise) had dwindled, as Martin, Sigrid and Berit are all well into adulthood and have outgrown the practical parental needs.

To my wife Ingrid; I love you for your encouragement, love, care and for "going up the route" by becoming a PhD before me, and encouraging me to do the same.

Tromsø, January 2017

Lars-Henrik Larsen

Lars-Henrik Larsen

# Abstract and list of research papers

In 2015, the European Arctic Seas (the Norwegian-, Barents- and Kara Seas and a sector of the Arctic Ocean north of Svalbard), housed more than 85% of all commercial ships movements in the Arctic. If fishing vessels operations is included, the share increases to more than 90%. Most of the commercial navigation is destination traffic to and from harbours around the European Arctic Seas. Trans-Arctic cargo shipping between the Pacific and Atlantic Oceans is insignificant. The receding Arctic Sea ice eases navigation in former heavy ice covered areas, but navigation is only in very few cases a target in itself. Drivers (export harbours, touristic sites, fishing resources) for shipping have to be present. One such driver is the petroleum development in Siberia, for which shallow depth ports along the Jamal Peninsula and Ob Bay in western Siberia are destinations for transported goods, and are expected to serve as major export harbours for petroleum in the near future.

Extraction of raw materials, fishing for northward expanding fish stocks, tourism and potentially increased use of trans-Arctic shipping routes will lead to increased navigation in the European Artic in the coming decades. Understanding of the environmental implications of increased Arctic shipping, against a back curtain of global warming, is an international theme of outmost importance. My dissertation aims at contributing to the knowledge needed for sustainable management of Arctic shipping.

In paper I, a scenario in which a fictitious, but realistic late autumn voyage takes an unwanted turn, is described. A container ship bound for Yamburg in Siberia grounds in the shallow Pechora Sea (South Eastern Barents Sea). The vessels crew is rescued, but the fictitious cargo, and the propulsion fuel, consisting of Marine Diesel Oil (MDO), is lost to sea. Clean-up shortcomings and potential environmental impacts are outlined.

The findings of the scenario are used as input to a mass-balance modelling (Ecopath) exercise of the transfer of energy and contaminants through the shallow water ecosystem of the Pechora Sea. The module Ecotracer is applied and demonstrates that Polycyclic Aromatic Hydrocarbons (PAH), stemming from a near momentary loss of MDO, could be traced all the way through the food-web (Paper II). The model exercise is mainly performed based on existing literature, supported by results from laboratory experiments on accumulation and excretion of PAH's in dominant invertebrate species of a coastal Arctic ecosystem (paper III). Finally, *in-situ* recordings from an accidental MDO spill in the Arctic (Skjervøy, Norway 70°N, December 2013) provided updated input parameters to the model.

In the laboratory experiment (Paper III), a dose dependent accumulation of PAH in red king crab (*Paralithodes camtschaticus*), scallop (*Chlamys islandica*) and blue mussel (*Mytilus edulis*) after a week of exposure to low sulphur MDO, was documented. After recovery for three weeks in clean water, a significant concentration reduction was found in the crabs. This experimental setup was designed to mimic a discharge from a point source like a wrecked vessel, running on MDO, and exposure of a predator and its potential prey organisms through water and food.

The fictitious journey of the container ship took place in late autumn (October). An established, but poorly substantiated notion has hitherto been, that the Arctic ecosystems are in a dormant, less active stage during the polar night, and thereby of limited sensitivity to any

human influence. By timing the fictitious incident late in the navigation season, knowledge of winter ecosystem processes is needed to fully understand the environmental impact.

To assess biological winter activity, analyses of fish stomach contents collected through five years of January sampling in the waters around Svalbard was carried out (Paper IV). Surprisingly active polar-night feeding in the dominant fish species polar cod (*Boreogadus saida*), haddock (*Melanogrammus aeglefinus*) and Atlantic cod (*Gadus morhua*) was documented (Paper IV), indicating that any perturbations from activities like shipping may prove as environmentally significant during January as during July.

The thesis finally discusses application of the results in research and management of Arctic shipping. Comments are made on applicability of restrictions on timing, types of vessels and cargo allowed, without jeopardizing the freedom of the high seas and the right to innocent passages for merchant and passenger ships, being the very basis for the 1982 United Nations Convention of the Law of the Seas (UNCLOS). The dissertation includes four papers:

Paper I Larsen L-H, Kvamstad-Lervold B, Sagerup K, Gribkovskaia V, Bambulyak A, Rautio R, Berg T E (2016) Technological and environmental challenges of Arctic shipping - A case study of a fictional voyage in the Arctic. Polar Research 35, 27977, http://dx.doi.org/10.3402/polar.v35.27977.

Paper II Larsen L-H, Sagerup K, Ramsvatn S (2016) The Mussel Path - Using the contaminant tracer, Ecotracer, in Ecopath to model the spread of pollutants in an Arctic marine food web. Ecological modelling 331:77-85. http://dx.doi.org/10.1016/j.ecolmodel.2015.10.011.

Paper III Sagerup K, Nahrgang J, Frantzen M, Larsen L-H, Geraudie P (2016) Biological effects of marine diesel oil on red king crab (*Paralithodes camtschaticus*) assessed through a water- and foodborne exposure experiment. Marine Environmental Research 119:126-135. http://dx.doi.org/10.1016/j.marenvres.2016.05.027.

Paper IV Larsen L-H, Cusa M, Eglund-Newby S, Berge J, Renaud PE, Falk-Petersen S, Varpe Ø (manuscript) Feeding activity and diet of gadoid fish in Svalbard waters during the polar night. (target journal: Polar Biology).

Contributions to each paper:

| | **Paper I** | **Paper II** | **Paper III** | **Paper IV** |
|---|---|---|---|---|
| Concept and idea | LHL, BKL, KSA, VGR | SIR, LHL | LHL, KSA, MFR | LHL, SEN, MCA |
| Study design and methods | LHL, KSA, RRA | SIR, LHL, KSA | KSA, MFR, PGE | LHL, MCA, SEN |
| Data gathering and interpretation | RRA, ABA, TEB, KSA, VGR | SIR, LHL, KSA | KSA, PGE | MCA, LHL, SEN |
| Manuscript preparation | LHL, KSA | LHL, SIR, KSA | KSA, JNA, MFR, LHL, PGE | LHL, MCA, JBE, PER, SFP, ØVA, SEN |

Lars-Henrik Larsen (LHL), Beate Kvamstad-Lervold (BKL), Kjetil Sagerup (KSA), Victoria Gribkovskaia (VGR), Alexei Bambulyak (ABA), Rune Rautio (RRA), Tor-Einar Berg (TBE), Silje Ramsvatn (SIR), Jasmin Nahrgang (JNA), Marianne Frantzen (MFR), Perrine Geraudie (PGE), Marine Cusa (MCA), Sam Eglund-Newby (SEN), Jørgen Berge (JBA), Paul E. Renaud (PER), Stig Falk-Petersen (SFP), Øystein Varpe (ØVA).

# List of abbreviations and acronyms

| | |
|---|---|
| AC | Arctic Council, International forum for cooperation among the eight Arctic nations, indigenous peoples organisations and non-arctic nations (observers) |
| ACAP | Arctic Contaminants Action Program. Working group under AC |
| ACIA | Arctic Climate Impact Assessment |
| AMAP | Artic Monitoring and Assessment Program. Working group under AC |
| AMSA | Arctic Marine Shipping Assessment, international evaluation of shipping in the Arctic |
| CAFF | Conservation of Arctic Flora and Fauna. Working group under AC |
| CNIIMF | Central Marine Research and Design Institute (St. Petersburg, Russia) |
| dwt | Dead Weight Tonnage, weight (in tonnes) of all the cargo, fuel, dry provisions, supplies, etc. carried on board a ship. |
| EPPR | Emergency Prevention, Preparedness and Response. Working group under AC |
| FNI | Fridtjof Nansen Institute, Lysaker, Norway |
| GHG | Green House Gasses, Compounds contributing to global warming when released to the atmosphere |
| HC | Hydrocarbons. Organic molecules containing Hydrogen and Carbon |
| HFO | Heavy Fuel Oil |
| HOCNF | Harmonised Offshore Chemical Notification Format. OSPAR guideline for classification of a chemical based on toxicity to marine organisms |
| IASC | International Arctic Science Committee |
| IMO | International Maritime Organisation |
| INSROP | International Northern Sea Route Programme |
| IOGP | International Oil and Gas Producers Association |
| ITOPF | International Tanker Owners Pollution Federation |
| LNG | Liquefied Natural Gas. Gaseous hydrocarbons cooled to liquid condition (minus 162 °C) |
| MARPOL | International Convention for the Prevention of Pollution from Ships |
| MDO | Marine Diesel Oil |
| MIZ | Marginal Ice Zone, biologically productive area along the edge of the Polar ice |
| MPA | Marine Protected Area |
| NEAC | North East Atlantic Current |
| NENT | National Norwegian Committee for Research Ethics in Science and Technology |
| NSR | Northern Sea Route, the Russian name for the North East Passage |
| NOR-VTS | Norwegian Oceanic Region Vessel Traffic Service in Vardø, Norway |
| OSPAR | Oslo-Paris convention on protection of the marine environment of the North-East Atlantic |
| OSR | Oil Spill Response. Any action involved in combatting spilled oil |
| PAH | Polycyclic Aromatic Hydrocarbons. Compounds found in oil, having varying toxic properties |
| $\Sigma PAH_{16}$ | Sum of 16 PAH compounds recommended by the American Environmental Protection Agency for inclusion in monitoring of PAH contamination. |
| PAME | Protection of the Marine Environment. Working group under AC |
| PM | Particulate Matter, soot and dust |
| PSSA | Particularly sensitive sea area |
| SDWG | Sustainable Development Working Group. Working group under AC |
| Sv | Sverdrup, unit for transport of water in an ocean current (1 Sv = $10^6$ $m^3$ $sec^{-1}$) |
| SAR | Search And Rescue (operation) |
| TBT | Tributyltin, anti-fouling agent no longer legal to apply on ships hulls |
| UiT | University in Tromsø, The Arctic University of Norway |
| UNCLOS | United Nations Convention of the Law of the Seas |
| VLCC | Very Large Crude Carrier. A tank vessel up to 250 000 dwt |
| ww | Wet weight |

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The papers.

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Copyright approval (paper II) for inclusion in printed version.

# 1. Introduction

This PhD project is part of a cross disciplinary research initiative, encompassing juridical, technological and environmental implications of navigation in a future warmer Arctic; A-lex, led by the Faculty of Law at UiT, and carried out in cooperation with Marintek and Akvaplan-niva. I have chosen to name my dissertation after the famous quotation of the Roman general Pompeius "Navigare necesse est - We have to sail", underlining how important ocean navigation historically has been, and still is, to trade and livelihood.

## 1.1 Research questions

The Arctic is, like the rest of the globe, currently experiencing extensive climate warming (IPCC 2014). The ice recedes, and profound changes to marine ecosystems, processes and species distribution and abundances in a warmer, less ice infested Arctic are predicted (Renaud et al. 2008; Drinkwater et al. 2010; Aschan et al. 2013; Nahrgang et al. 2014). Reduced extent of the Arctic sea ice eases navigation. Fishing, cruise traffic and transport of raw materials and commodities gets easier. The Arctic offers transit routes which significantly reduce the sailing distance between Europe, Asia and America, thereby saving time and fuel. The avoidance of pirate ridden bottleneck regions like the Aden Bay and the Malacca Strait along the traditional Ocean routes also speaks in favour of Arctic navigation routes.

Provision of knowledge on impacts of Arctic shipping is essential for responsible management of one of the least studied areas of the globe. The main purpose of my dissertation is thus to contribute to the joint understanding of how and to what extent, shipping is influencing Arctic marine ecosystems. In this thesis, the main question is: What are the key bio - environmental issues related to current and future shipping in the European Arctic Seas? This overall question again has led to four specific research questions, which I have addressed in my research:

**1. Arctic shipping of today – which scenarios may unfold?**
A survey of today's shipping patterns, vessel types and navigation routines was used to develop a fictitious, but realistic navigation scenario. The scenario includes the loss of a cargo vessel on a late October Arctic destination voyage (paper I), and illustrates the complexity and multitude of potential environmental impacts arising from shipping.

**2. How is a contaminant (PAH) transferred through an Arctic ecosystem?**
Most regions of the Arctic seas are poorly covered by environmental data and information. Against a chancing background, environmental data rapidly become outdated and loses temporal validity. This may partly be counteracted by use of models in assessment and management, however, still under the condition that relevant input data are available. The wreckage incident is used as input to a modelling exercise to provide information on how a contaminant may be spread through an Arctic ecosystem (paper II).

**3. Does a key species of the ecosystem (the red king crab (*Paralithodes camtschaticus*)) accumulate and excrete PAH after a single exposure to oil?**
Experimental ecotoxicology provide input to predictive modelling. We exposed red king crab to PAH from MDO in a single exposure experiment, mimicking a momentary loss of propulsion fuel from a wrecked ship (Paper III). The experiment was carried out in Tromsø at late autumn Arctic climate conditions.

**4 What is the feeding activity in key fish species during polar night?**
Seasonality is a key element in the Arctic ecosystems. The fictitious wreckage took place in late autumn in an important winter spawning area for a key fish species, the polar cod (*Boreogadus saida*). In a warmer Arctic, the navigation season is expected to extend into the dark period of the year, a period from which limited knowledge on the ecosystems is available. In paper IV, winter feeding and ecology of fish during the polar night are presented, to provide updated input to future risk and impact assessments.

## 1.2 The European Arctic Seas

Defining the Arctic as the areas of the globe north of the Arctic Circle (approx. 66°33'N), the European Arctic Seas is a collective name for the waters off East Greenland-, the northern part of the Norwegian Sea, the Barents- and the Kara Seas, and the part of the Arctic Ocean located North of Svalbard (Figure 1).

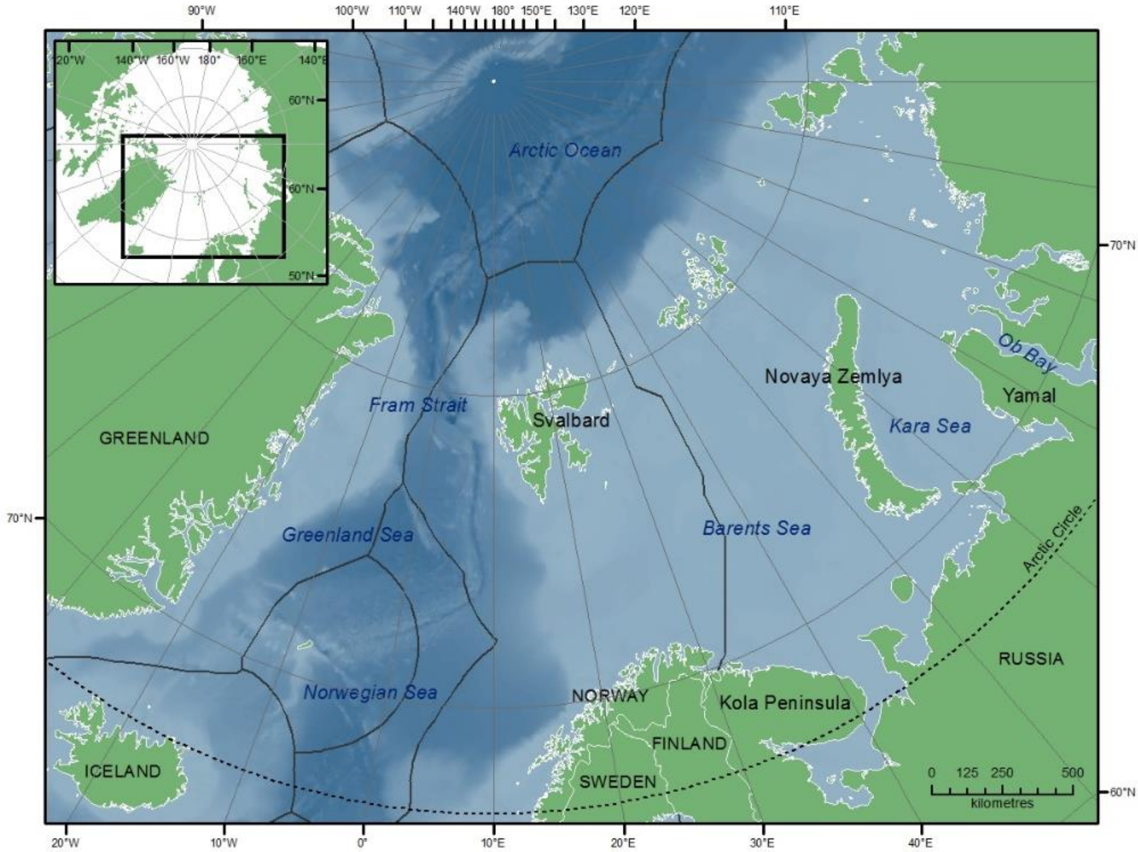


Figure 1 The seas of the European Arctic. Black lines indicate international maritime boundaries.

The North East Atlantic current (NEAC) provides inflow of warm and saline water to the Norwegian Sea from the south-west, mainly between the British Isles and the Faroes (the Faroe-Shetland channel). In a review by Blindheim and Østerhus (2005), this inflow is reported to vary from 2 - 12 Sverdrup (1 Sv = $10^6$ $m^3$ $sec^{-1}$), averaging 7.7 Sv. The NEAC thus transports huge amounts of water and heat energy to this part of the Arctic.

West of Svalbard, in the Fram Strait (Figure 1), the northward transport of water and heat in the West Spitsbergen Current (the northward extension of the NEAC) is reduced to 3 - 5 Sv (Schauer et al. 2004). This flow is counteracted by a southward flow of 3 - 4 Sv of Arctic water and ice in the western part of the Fram Strait along the Greenlandic coast (Foldvik et al. 1988; Fahrbach et al. 2001). Also the Barents Sea receives a branch of the inflow of warm Atlantic water, and an average inflow of 3 Sv along the coast of Northern Norway and the Kola Peninsula is reported (Ozhigin et al. 2011). The outflow of Polar water and ice through the Western Fram Strait provides a very different environmental setting compared to the Barents Sea and the Eastern Fram Strait, rendering most of the east coast of Greenland inaccessible to non-icebreaking ships year round (Figure 2).

The Atlantic water inflow to the European Arctic Seas is responsible for much of the rather hospitable Arctic climate of Northern Norway, Svalbard and coastal parts of North West Russia. It provides for Murmansk having an essentially ice free harbour, and Svalbard being accessible for ships year round. Due to the inflow of warm, nutrient rich Atlantic water, most parts of the European Arctic Seas are characterised by rich biological production (Falk-Petersen et al. 2000). This again triggers rich fisheries, and together with raw material extraction, provides basis for the largest human population centres in the entire Arctic.

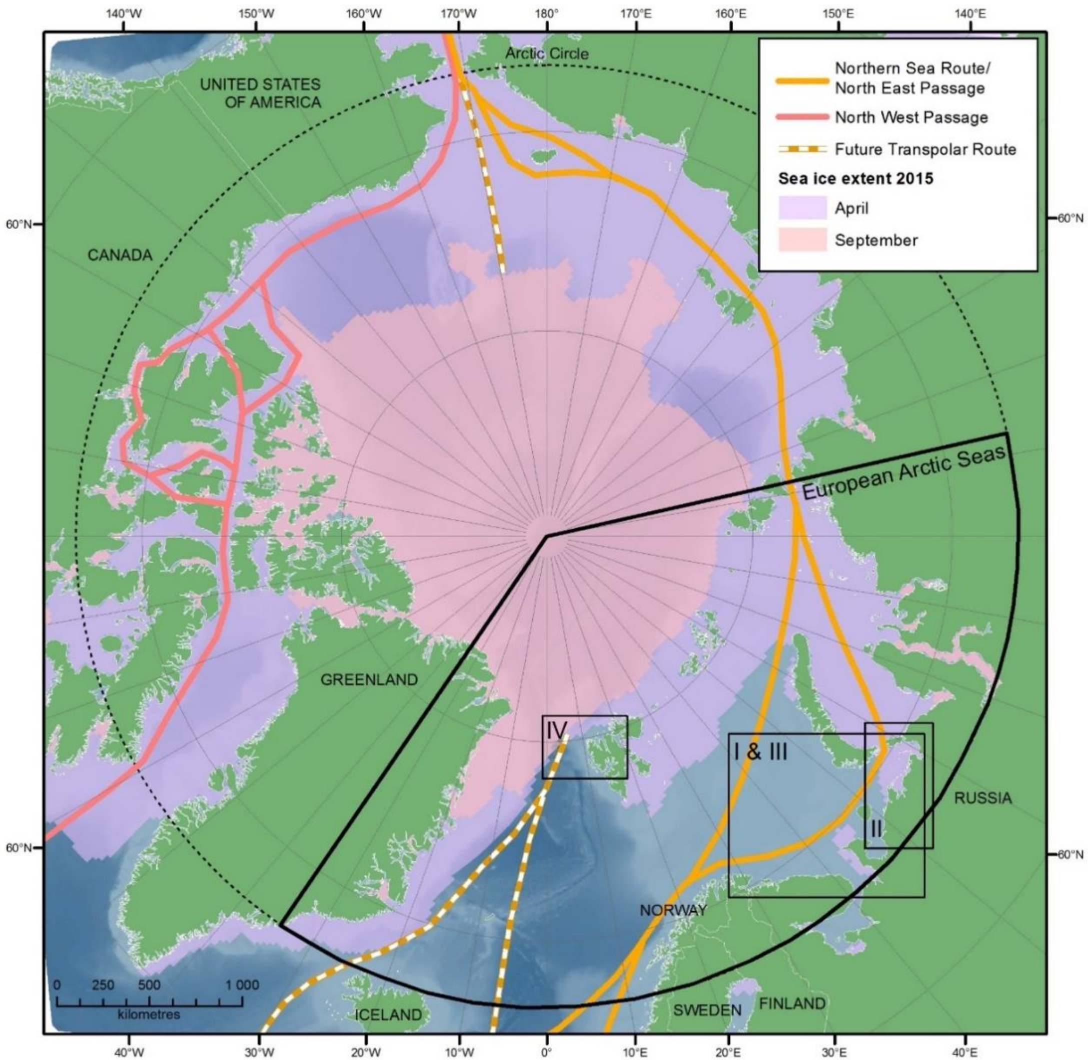


Figure 2 Current and potential future trans Arctic shipping routes. Ice extent in April 2015 and September 2015 indicated (National Snow and Ice data Centre 2016a). The extent images show the areas covered by ice at greater than 15 percent monthly mean concentration. The area around the North Pole that the satellite does not image is assumed to be covered by ice at more than 15 percent concentration. (http://nsidc.org/data/seaice_index/more-about-monthly.html). Squares with roman numerals indicate approximately geographic location of research paper I – IV of the dissertation.

## 2. Global and Arctic navigation

Ocean navigation has been important to mankind for millennia. It can be traced back to the ancient Greek navigators like Odyssey and the Roman galleys dominating the Mediterranean and maintaining the power of the entire empire. The Vikings went far abroad from the Nordic countries, raiding and trading in Western Europe and Northern Africa. During the 16$^{th}$, 17$^{th}$ and 18$^{th}$ centuries, the cross oceanic traffic was carrying commodities like sugar, silk, rum, spice and whale oil from the New World, the Arctic or Asia home to the empires of Europe.

The early 20$^{th}$ century saw ocean whaling around Antarctica, global maritime warfare and by today, the merchant fleet numbering more than 50 000 commercial vessels worldwide, transports virtually everything across the oceans in still increasing amounts to support our consumption-based societies. Major shipping-routes have been established and used through generations – and new routes have been developed. Particularly the opening of the Suez Canal between the Red Sea and the Mediterranean in 1869, and the Panama Canal in 1914, interconnecting the global oceans, boosted shipping and reduced sailing distances significantly.

Since the late 20$^{th}$ century, a warmer climate has led to a decrease in the ice cover of the Arctic Polar Seas, and observations of new, record breaking minimal summer ice extents have frequently been reported (Vinje 2001, Arrigo et al. 2008, Falk-Petersen et al. 2015, NSIDC 2016b). Also model predictions indicating the total disappearance of the Polar Ice Cap during summer within the first half of the 21$^{st}$ century have recently made headlines (e.g. Kramer 2013). With less ice, shipping through, but first of all around, the Arctic Ocean, between the North Atlantic and the North Pacific becomes more feasible, and therefore also of commercial interest. A new region of the globe is becoming of increased relevance and interest as a host for shipboard transportation; the cold and hitherto nearly inaccessible Arctic Seas.

The European Arctic Seas in 2015 were host to more than 85 % of all ships movements (excl. fishing vessels) in the Arctic (Figure 3).

Most of the navigation in the European Arctic Seas consists of destination traffic to and from harbours of the region (Figure 4). However, navigation is seldom a target in itself, but the most efficient way to transport goods, raw material and commodities to markets and communities worldwide. An important driver for increased destination traffic in the European Arctic Seas is the petroleum development offshore in the Barents- and Kara Seas, and onshore in Siberia. Ports along the Yamal Peninsula and Ob Bay in Russia (Figure 1) are destinations for transported goods, and are expected to develop into major hydrocarbon export harbours shortly (Bambulyak et al. 2015).

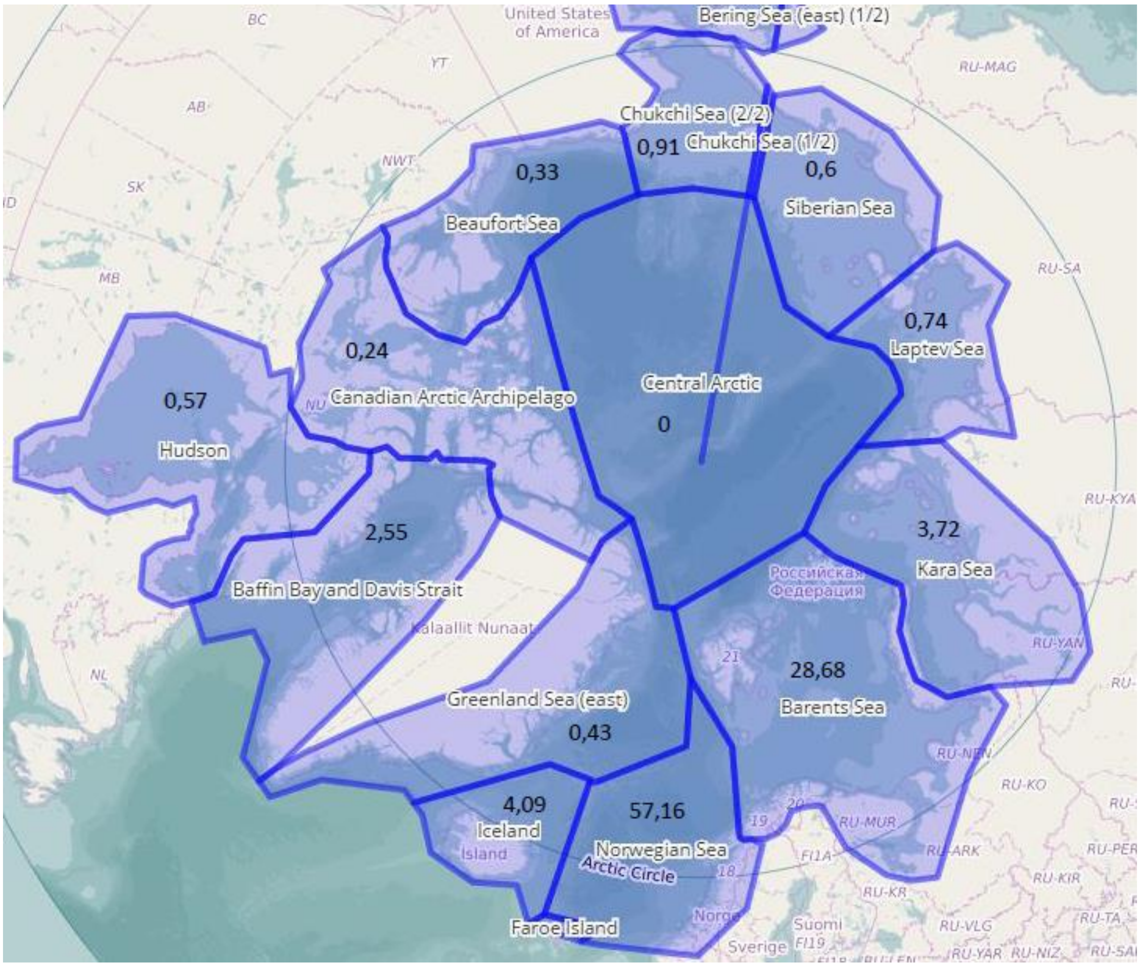


Figure 3 Regional percentages of recorded ships movements (excl. fishing vessels) in 2015. Data recorded and provided from the Norwegian Oceanic Region Vessel Traffic Service (NOR VTS) in Vardø, Norway.

Increased transit shipping through the Arctic may partly replace navigation along existing non-Arctic routes. However, the majority of navigation in the Arctic is, and is for a foreseeable future expected to be destination traffic (Arctic Council 2009). Arctic transit shipping is, despite expectations and optimistic views, still insignificant, peaking at 71 travels along the entire Northern Sea Route (NSR) in 2013 (Jacobsen and Henriksen 2015), dropping again to only 18 transit travels in 2015 (PAME 2016).

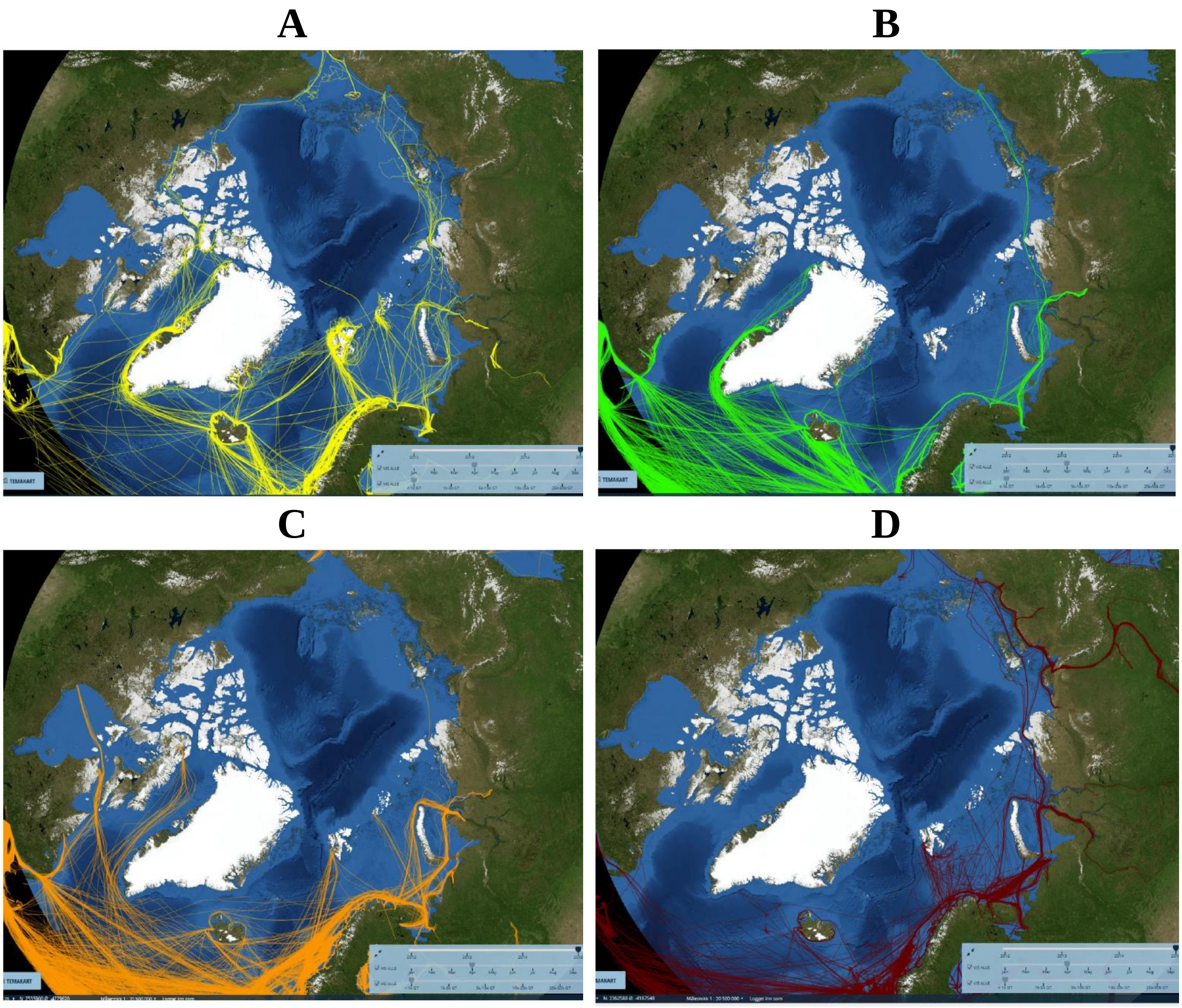


Figure 4 Geographic distribution of ships movements in the Arctic 2015. Data recorded and provided from the Norwegian Oceanic Region Vessel Traffic Service (NOR VTS) in Vardø. Vessels above 5000 dwt. A: passenger vessels, B: container vessels, C: bulk carriers, D: oil tankers.

Strong seasonality in abiotic conditions is a key feature of the Arctic, governed by the annual distribution of solar irradiation. The oceanographic winter (the period with lowest sea water temperature) occurs in the European Arctic nearly three months after the winter solar irradiation minimum, i.e. the coldest month with the largest sea ice extent is March/April, and the oceanographically warmest month with minimum ice is September (Falk-Petersen et al. 2000, 2015).

Lighter ice conditions in the Arctic Seas is accordingly expected to occur in the relatively warm autumn and early winter. E.g. future periods with easier navigation in the European Arctic is most likely to include November – January, meaning increased navigation during the period of the year, when the sun is below the horizon (the polar night). Understanding the winter biology and ecosystem conditions during polar night is thus becoming of increasing importance for environmental management.

## 2.1 Increasing awareness of environmental impacts of shipping

No doubt that both the Norwegian pioneers Roald Amundsen and Fridtjof Nansen considered the risks before departing on their historic, late 19th early 20th century Arctic voyages. However, the concept "risk" was at that time related to the abiotic conditions like wind, ice, darkness and fog hampering their travel and posing a threat of loss of vessels and crew. The notion that this type of activity itself posed a risk to nature was not conceived until half a century later.

After the second world war, world trade boomed and sea transport gradually gained more importance (Walter 2012). Despite the war having seen large numbers of vessels lost in both the Atlantic and the Pacific, it was not until the 1960s that focus gradually evolved on both the operational and accidental impacts of shipping on the marine environment. The Norwegian explorer and scientist Thor Heyerdahl made observations and recordings of oil and tar floating in the Atlantic during the Ra I and Ra II papyrus boat expeditions in 1969 and 1970 (Heyerdahl 1971). These results made headlines and were among the main topics at the United Nations environmental conference in Stockholm in 1972, where the Declaration of the United Nations Conference on the Human Environment was adopted (UNEP 2016) and was among the first major, international eye-opener on marine pollution issues. The Stockholm conference paved the way for the establishment of the Oslo Paris Commission (OSPAR) on abolishing dumping of waste at sea (See chapter 2.2.2).

The implications of a severe shipping accident with a major oil spill had become painfully clear in 1967. On 18 March, the tanker *Torrey Canyon*, carrying 117 000 tons of crude oil plus bunkers, ran aground in the English Channel and became wrecked (Walsh 1968). At that time, this was the largest vessel ever to be wrecked, and the loss of all her cargo to the sea draw much (justified) attention to the environmental risk associated with shipping. As a result of the *Torrey Canyon* wreckage, the International Maritime Organisation (IMO)[1] called an extraordinary session of its council and decided to convene a conference to prepare an international agreement addressing contamination of the sea, land and air from ships. Thus the International Convention for the Prevention of Pollution from Ships (MARPOL) was established.

The *Torrey Canyon* accident, and the following *Amoco Cadiz* wreckage on the 16 March 1978, where 223 000 tonnes of crude was spilled (Conan et al. 1982) off the coast of Brittany, further increased awareness of the risks posed by, first of all, large crude oil carriers. The concept of pro-active environmental risk assessment and risk management, combined with technical requirements for merchant ships (including crude carriers) was now approaching, and from the 1970's until today, the number of large, catastrophic oil spills from ships has decreased (Figure 5).

In Alaska, at 60°N, in the Northern Pacific, the *Exxon Valdez* wreckage (24 March 1989, Prince Williams Sound, USA, approx. 44 000 tonnes of crude oil discharged) took place in ice-infested waters, but not strictly within the Arctic. However, this incident severely challenged the response operations due to its remoteness, harsh climatic conditions and difficult access, a feature shared by many sites along current and future Arctic navigation routes (ref paper I).

[1] IMO, UN-Intergovernmental convention on safety of shipping, established in 1948, and entered into force in 1958. For more info, see: www.imo.org.

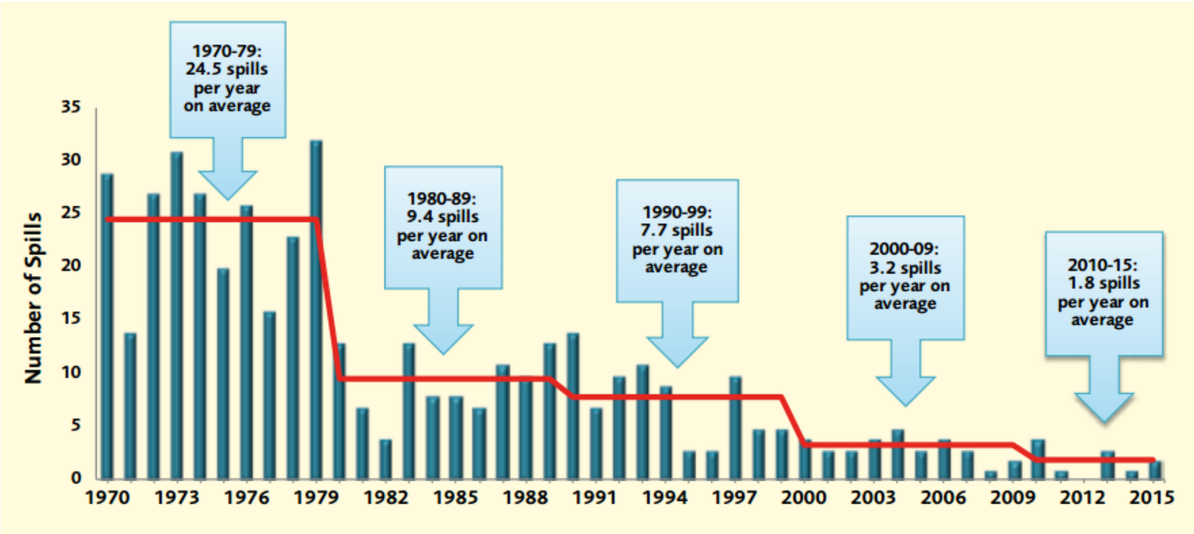


Figure 5 Trend in number of large oil spills to the world oceans from shipping 1970 – 2015. Source: ITOPF 2016. Note that the minimum cut-off value is 700 tonnes of spilled oil, which is so high that none of the incidents historically having oiled Norwegian beaches (Boitsov et al. 2012) qualify for registration.

Major oil spills create headlines, cause profound environmental impacts, and are often the single event needed to trigger management actions on strategic level. However, major oil spills are not everyday scenarios, and the impacts of non-catastrophic, more frequent accidental events have gradually gained more attention in assessments of human influence to nature. Some recent key assessment and evaluation initiatives focusing on shipping in the Arctic are presented.

## 2.2 Assessments of Arctic navigation

Russia manages nearly half of the Arctic Seas, and has long experiences with Arctic navigation to and from the industry sites and harbours in Siberia. Since the 1991 dissolution of the Soviet Union, several international assessment programmes have included Arctic shipping activities in holistic assessments of environmental impacts of human activities. These include:

### 2.2.1 International Northern Sea Route Programme (INSROP) 1993-99

The first truly international assessment initiative related to Arctic shipping was the Russian-Norwegian-Japanese "International Northern Sea Route Programme" (INSROP), which ran from 1993 to 1999 (Østreng et al. 1999). The program was carried out by a large, international team of researchers, and was led by the Fridtjof Nansen Institute (FNI) Norway and the Central Marine Research and Design Institute (CNIIMF) Russia. The Japanese Ships and Ocean foundation and 12 international sponsoring organisations provided funding. INSROP consisted of four thematic sub-programmes, 1: Natural conditions and ice navigation; 2: Environmental factors; 3: Trade and commercial shipping aspects and 4: Political, Legal and Strategic factors. Results and findings were published through peer reviewed INSROP working papers and articles in international scientific journals.

The environmental subprogram of INSROP was led by the Norwegian Polar Institute, and aimed at preparing an Environmental Impact Assessment (EIA) of year round icebreaker assisted transit (and destination) navigation along the Northern Sea Route (the North East Passage, Figure 2). The design and focus of INSROP was drafted by an expert meeting in Tromsø in October 1992 (Simonsen (ed.) 1992), and the goal of developing an EIA was achieved when INSROP Working Paper nr 163 was published (Thomassen et al. 1999); concluding (quote):

- "Except for ports, harbours, shipyards etc., there is no historical evidence that navigation itself has proven significant impact on the marine environment. The same can be applied to NSR. Sailing on the NSR has been carried on for decades. Even if significant local contamination of ports and harbours, accumulation of waste and garbage on the shore etc., are documented, there is no evidence that the large scale trends of some declining ecosystem component populations have been caused directly by this sailing.
- Increased sailing frequency however, will inevitably increase the risk for ship accidents, and correspondingly increase the risk of accidental release of oil. Large scale oil spills can have deleterious impact on the marine environment. The most vulnerable period is assumed to be during the most productive season, e.g. the late spring-summer, which also correspond to the most frequent sailing period."

INSROP was completed in a period with significant changes in the Russian society, and before the issue of global warming and climate change had fully entered the international scientific agenda. INSROP was an immense, cross disciplinary effort, and provided a strong foundation for cooperation between Western, Russian and Japanese researchers within a wealth of disciplines. This is likely the most significant contribution from INSROP. A retrospective summary of INSROP is provided by Brubaker and Ragner (2010).

### 2.2.2 OSPAR Commission study 2009

OSPAR, the cooperation between 15 countries of Western Europe, address issues of protecting the marine environment of the North-East Atlantic. OSPAR's area of coverage stretches from the North Pole to Gibraltar (36°N; 5°W), and from the Barents Sea to the waters west of the Azores (38°N; 28°W). OSPAR is the 1998 merger of the 1972 Oslo convention on banning of dumping of waste to the sea, and the 1974 Paris convention on reduction of discharges to sea from land based contamination sources. Approximately every 10 years, OSPAR publishes quality status reports (QSR's) summarising the status of a set of contamination and impact indicators within its area of responsibility. In preparation for the latest (2010) QSR, OSPAR in 2009 published an "Assessment of impacts of shipping on the marine environment" (OSPAR 2009). In addition to focus on discharges of contaminants from ships, this assessment pinpointed ships noise and ship collisions with marine mammals as areas needing more attention from the member countries.

### 2.2.3 The Arctic Council (AC)

Based on the opening up of the Soviet Union and the establishment of the International Arctic Science Committee (IASC), the Finnish initiative of 1989 named after the city Rovaniemi (Elferink 1992), was the first strong initiative on international cooperation on Arctic Environmental issues in general. With Finland as lead in this Arctic Environmental Protection Strategy (AEPS), the first ministerial conference, including all eight Arctic countries, was held in Rovaniemi in 1991. On a regional scale, the Barents Euro Arctic Cooperation was established in 1993, while the Arctic Council (AC) was established in 1996 and was appointed overall responsibility for the four working groups established under the AEPS. The content and mandate for the AC is given in the "Declaration on the Establishment of the Arctic Council" signed in Ottawa, Canada, 1996. The AC has gradually developed to be the most prominent cooperation arena for the eight Arctic nations and representatives from the indigenous people's associations. A number of non-Arctic territory countries have recently joined the AC as observers.

The work of the AC is carried out in permanent working groups, currently six, addressing key issues of management of the Arctic. The working groups are; the Arctic monitoring and assessment program (AMAP), the Protection of the Arctic Marine Environment (PAME), the Conservation of Arctic Flora and fauna (CAFF), the Emergency Prevention, Preparedness and Response (EPPR), Sustainable Development Working Group (SDWG), and the Arctic Contaminants Action Program (ACAP). For further information on responsibilities and areas of work, see http://www.arctic-council.org/index.php/en/.

### 2.2.4 The Arctic Marine Shipping Assessment (AMSA)

While the OSPAR and INSROP programmes focused on geographically limited areas of the Arctic, the first circumpolar assessment of impacts of Arctic shipping was the four year (2006-2009) Arctic Marine Shipping Assessment (AMSA), led by the PAME working group (Arctic Council 2009).

AMSA was initiated by the AC, based on the AMAP led Arctic Climate Impact Assessment (ACIA) from 2004, stating that "Reduced sea ice is very likely to increase marine transport and access to resources". In this broad assessment, 17 specific recommendations on actions to be taken by the AC member states were presented. Status on implementation of these recommendations is followed up in biannual progress reports (PAME 2013; 2015). AMSA highlights various oil spills, collisions between mammals and ships, the introduction of invasive non-native species and emissions to air as the most important potential impacts from Arctic shipping. The recommendations given on the protection of Arctic Peoples and the Environment are found here: http://www.pame.is/index.php/projects/arctic-marine-shipping/amsa.

AMSA is the most comprehensive and authoritative assessment related to Arctic shipping, and the recommendations presented are followed up in assessments and through basic scientific research carried out by research institutions and universities worldwide. AMSA was followed up with two major initiatives. A circumpolar identification of areas of heightened ecological and cultural significance was presented by the AC working groups AMAP, CAFF and SDWG in 2013. This assessment identifies nearly 12 millions square $km^2$ of the Arctic Seas as being of heightened ecological and cultural significance (AMAP/CAFF/SDWG 2013). The total sea area north of the Arctic circle is 13.4 million $km^2$.

The second AMSA follow up was the establishment of the "Code for ships design and navigation in Polar Areas" (IMO 2016a), named the Polar Code, which regulates ship design, environmental performance and navigation in both Arctic and Antarctic waters. This regulation entered into force on 1 January 2017.

### 2.2.5 Generic impacts of shipping

In evaluations of shipping influence on the marine environment, the duration, geographic extent and the severity of an impact are generally made in relation to the ecosystems being influenced.

<u>Temporal extent</u> of an impact may vary from "momentary" (e.g. the noise of a ship passing), leaving no visible traces except for potential changes in localisation of animals scared away from the track, to "permanent", for example the establishment of a harbour.

Spatial extent of an influence is evaluated on a scale from "local", in which only a small geographic area (e.g. an anchoring location or icebreaker assisted navigation along a segment of an ice infested route) is influenced. The other extreme on a geographic extent scale is an impact with global influence, such as emissions of $CO_2$.

The final assessment scale requires ecosystem knowledge, and is related to how extensive species, populations and ecosystem processes are influenced by an event. A measure frequently applied includes restitution time (time required for populations or ecosystems to re-establish to pre-incident conditions). Restitution time may extend from immediate restitution, e.g. a population of animals returning to pre-navigation distribution and activity when a ship has passed, to the other extreme where an introduced non-native species has established and created a new biological balance, and the ecosystem never returns to pre-incident conditions.

Irrespective of destination, type of cargo or time of the year, a generic suite of impact factors are associated with shipping. Some of the impacts will occur ("operational impacts"); while some are "potential" and may only occur in case of an unwanted event. Each impact factor will influence ecosystem processes, biodiversity and human harvest of renewable resources to varying extents. Based on a literature survey, environmental impact factors related to shipping, and focal topics for each impact factor in the Arctic are presented in Table 1.

Referring to table 1, my research includes developing a scenario addressing Arctic navigation through ice free waters, but as the scenario develops, it also includes accidental release of propulsion fuel and cargo. Spread of contaminants through the food web is modelled, experimental provision of input data on accumulation and excretion of PAH in key invertebrate species, and provision of data on the ecosystems in polar night condition is also addressed.

Table 1 Generic environmental impact factors related to shipping, and focus topics in the Arctic (not in prioritised order).

| | Shipping activity | Environmental impact | Focus in the Arctic | Reference |
|---|---|---|---|---|
| Physical disturbances | Physical passage (innocent passage) | Physical disturbance | Breaking of ice. Exposure of under-ice organisms to e.g. avian predators | Divoky (1976) |
| | Noise and vibrations | Scaring of animals | On-ice whelping grounds (seals, walrus), whales, fish spawning areas | Dooling & Therrien (2012); Erbe (2012); Mckuin and Campbell (2016) |
| | Breaking of ice in shore-leads | Thinner ice, broken ice floes | Indigenous fishing and livelihoods altered (social impact) | Cameron (2012) |
| | Navigation in shore leads, polynya and in darkness | Collisions with marine mammals | Sluggish and slow moving Arctic marine mammals | Huntington (2009) Reeves et al. (2012) |
| Operational discharges and emissions | Emissions of soot, black carbon, $SO_2$ particles incl. on-board incineration of waste | Climate warming, smothering | Local increased melting of ice | Winther et al. (2014); Aliabadi et al. (2015) |
| | Emission of $CO_2$ and other greenhouse gases (GHG) | Climate warming Ocean acidification | Potential ecosystem level impacts | Corbett et al. (2010) |
| | Waste water (grey- and black water) | Nutrients, contami-nants, bacteria | | Loehr et al. (2006) |
| | Garbage (organic/ plastic/ cardboard/ plywood/ metal) | Littering | Plastic waste in global focus. Micro plastics | Lusher et al. (2015) Wilewska-Bien et al. (2016) |
| | Oil, operational discharge | Pollution | Smothering, accumulation in fat based food chains | Ferrano et al. (2009) |
| | Antifouling agents (TBT and other pesticides) | Contamination, sex change in molluscs | Mostly solved by TBT ban | Dafforn et al. (2011) |
| | Settling organisms on ships hulls | Introduction of alien species. Biodiversity impacts | Potential ecosystem level impacts | Chan et al. (2015) |
| | Ballast water | Introduction of alien species. Ecosystem level impacts | Potential ecosystem level impacts. | Scriven et al. (2015) Ware et al. (2016) |
| Infra-structure | Harbours, Lighthouses, navigation aids | Dredging, construction works | Local habitat modifications | |
| | Sea charting | Vessel traffic in uncharted waters | Risk of wreckage of charting vessels, safer post survey navigation | Borgerson (2008) |
| Accidents | Loss of vessel, decay of wreck | Physical decay and long term release of e.g. metals, fuel and residues | Long term emissions to e.g. coastal communities at wreckage site | Schroeder et al. 2008 |
| | Loss of cargo (containers, liquid bulk, dry bulk) excl. petroleum | Pollution, navigational hazards (e.g. floating cargo/ containers) | Most ecosystem components influenced | Neuparth et al. (2011), Breivik et al. (2012) |
| | Loss of propulsion fuel and petroleum cargo | Smothering, toxicity, bioaccumulation | Most ecosystem components influenced HFO restrictions, area restrictions | Paine et al. (1996), Webster et al. (1997), Perez et al. (2008), Muncaster et al. (2016) |
| | Impacts related to Search and Rescue (SAR) | Helicopter traffic, ships traffic | Helo/rescue vessels in sensitive areas. | Rødseth et al. (2015) |

# 3. Arctic Marine Ecosystems

Knowing the design of vessels, types of cargo, intended sailing routes and types of propulsion fuel is only half the story of assessing the environmental impacts of shipping. Understanding the annual and seasonal variation in distribution and abundance of ecosystem components of the Arctic is of equal importance. Arctic marine ecosystems have several features, making them different from temperate or warmer areas, and within which our understanding still needs improvement.

## 3.1 Seasonality and variation in abiotic conditions

In the Arctic, large variations in light and temperature conditions are encountered. Light conditions vary from months of continuous darkness to midnight sun (For definitions and overview, see Berge et al. 2015a). Most of today's shipping in the European Arctic Seas occurs south of approx. 75°N (Figure 4). At these latitudes, the Polar night include civil polar night (the period with the sun between 12 and 6 degrees below the horizon) for approximately two months (ref paper IV), and an equal period of summer midnight sun and continuous daylight.

The variations in solar irradiation causes strong seasonality in Arctic marine ecosystems (Węsławski et al. 1988), and pronounced seasonal variation in primary production, organisms' energy storage and trophic transfer (Falk-Petersen et al. 1990). Based on an anticipated low primary productivity during the polar night, the marine ecosystems of the Arctic have until recently been considered dominated by dormancy and hibernation during the dark period. This notion is currently under scrutiny, and recent surveys of the waters around Svalbard have documented that the winter is sustaining biological activity at most trophic levels (Berge et al. 2015a and b). Thinner ice, earlier melting, and later freeze-up expectedly associated with a warmer Arctic, will strongly affect the light regime in the surface water layers and in shallow benthic habitats. Earlier and deeper light penetration will stimulate primary production (Søreide et al. 2010).

The European Arctic is unique compared to the rest of the Arctic Seas, as advection of heat energy from the NEAC plays a major role in this region. In the light of major abiotic forcing, seasonality, sensitivity, structure and function of ecosystems varies; The open seas, shallow coastal areas, the edge of the polar ice, deep-water shelf systems all differ in key processes and plant and animal populations. The term Arctic Ecosystem is thus not a uniform concept, but is applied to a vast variety of habitats with unique floral - and faunal assemblages.

To illustrate the geographic heterogeneity and temporal variability in distribution and abundance, three ecosystems of the European Arctic seas are briefly introduced; the shallow coastal waters (ref. paper II), the ecosystem along the edge of the polar ice, and the Atlantic influenced waters of the Eastern Fram Strait and western Svalbard (ref. paper IV).

## 3.2 Coastal ecosystems

The seas of the European Arctic house coastal habitats of strongly varying topography, wave exposure, water depth (Figure 6), and with a vast variety of associated biological resources (Sakshaug and Kovacs 2009). Ice scouring limits distribution and abundance of intertidal flora and fauna (Gulliksen and Svensen 2004, Gulliksen et al. 2009). Seasonal runoff of freshwater with high turbidity from rivers and glaciers (Andersen 1989) and seasonal ice cover (Arrigo et al. 2008; Popova et al. 2010) limits both planktonic and benthic primary production in coastal ecosystems.

The coastal ecosystems thus endure extreme abiotic seasonal variation, however, adapted species often occur in high densities, like the numerous bivalve mussels and polychaete worms recorded from shallow sublittoral habitats in the Pechora Sea (South Eastern Barents Sea, 68-71°N; 46-59°E, paper II) (Denisenko et al. 2003). Decreasing species richness and biomass of benthic species towards sediment producing tidal glaciers, like the ones in inner Kongsfjorden in Svalbard (78°N;12°E), has been observed (Voronkov et al. 2013). In Kongsfjorden, Bartsch et al. (2015) found an increase in macro algae in shallow regions of the fjord, explained by higher sea temperature and less sea ice. Similar patterns are also expected in other areas with similar habitats in a warmer Arctic (Krause-Jensen and Duarte 2014; Weincke and Hop 2016).

Climate warming also influences coastal ecosystems and habitats in the Arctic. A study comparing rocky littoral habitats in Svalbard after 20 years of climate warming revealed a twofold increase in the number of macroorganisms, a threefold increase in the biomass of macrophytes, and an upward shift in algae occurrence. Expansion of subarctic boreal species, accompanied by a retreat of Arctic species was also reported (Węsławski et al. 2010).

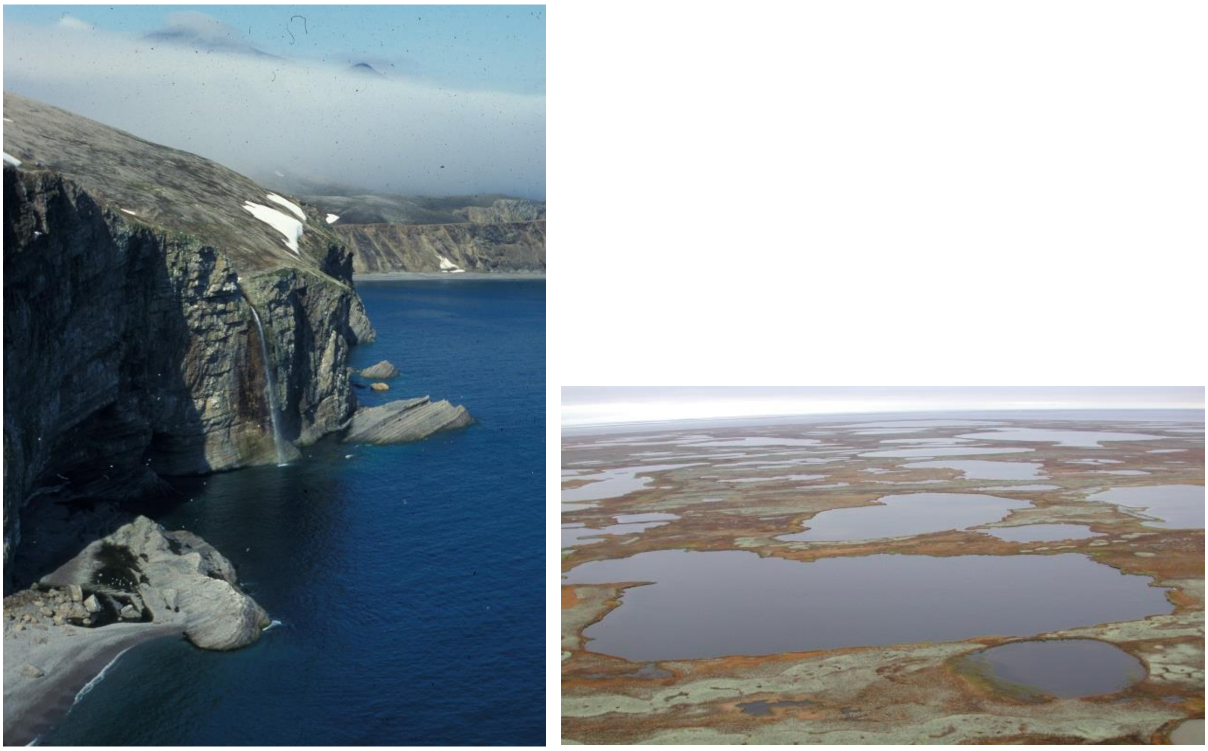

Figure 6 Variations of coastal habitats of the Barents Sea. Left: Bjørnøya coastline (74°N,19°E). Right: The coastline of the Pechora Sea at 68°N; 55°E. Photo: Guttorm Christensen and Salve Dahle, Akvaplan-niva.

## 3.3 The edge of the Polar Ice cap

Barber et al. (2015) state, in a pan-Arctic review, that the marginal ice zone (MIZ) of the Arctic Ocean is changing rapidly due to the warming climate. This leads to reductions in sea ice extent and thickness. Increasingly larger areas of open water during spring and summer occur, favouring higher pelagic primary and secondary production. The Ice edge ecosystem is geographically variable, and houses a unique flora and fauna (Figure 7). In case of an oil spill, the edge of the ice is the first area to be exposed e.g. to an oil slick floating on the open sea. Navigation along the ice edge is potentially attractive for vessels searching for trans-Arctic passage without heavy ice breaker assistance (ref Figure 2).

During spring, the melting ice forms a layer of low saline water, often 10 - 30 m thick, stabilising the water column along the ice. The vertical circulation is limited, keeping the phytoplankton organisms in the photic zone (Sverdrup et al. 1942; Strass and Nöthig 1996). This provides high primary production along the ice, being grazed upon by zooplankton, ice fauna and fish (Falk-Petersen et al. 2007). The polar cod and capelin (*Mallotus villosus*) feed along the MIZ, as do seabirds and seals, the latter also use the ice as haul out. The MIZ in the Barents Sea is the main feeding ground for the polar bear *Ursus maritimus* (Andersen and Aas 2016).


Figure 7 The Marginal Ice zone ecosystem in the Barents Sea (Photos: Bjørn Gulliksen, Rune Palerud, Christian Lydersen, Cathrine Stephansen and Michael Carroll). Compiled by the author.

## 3.4 Mixed Water inflow area; The eastern Fram Strait

High primary productivity associated with inflowing Atlantic water makes the Barents Sea rich and biologically diverse. However, outside the influence of the Atlantic water, primary productivity in the European Arctic Seas (Figure 1) is significantly lower (Reigstad et al. 2011 Figure 8), partly due to the presence of sea-ice. However, fuelled by winter upwelling of nutrient rich water, there is high levels of primary production in the Eastern Fram Strait, which provides for a lipid-based food chain, mediated primarily by calanoid copepods (Falk-Petersen et al. 2007, 2008) and leading all the way up to the large baleen whales, e.g. bowhead (*Balaena mysticetus*).

Productive marine ecosystems provide for human harvest. Through harvest of marine mammals and fish, man has impacted the European Arctic Seas through the removal of biomass for centuries. Examples are the 16th -18th centuries harvest of whales (Falk-Petersen et al. 2015), the 1970's extreme harvest of capelin (Gjøsæter et al. 2012) and the continuous harvest of the world's largest cod stock from the productive Barents Sea. Most ship movements in the Barents Sea are fishing vessels, and there is a clear overlap between areas with high primary production and fishing activity (Figure 8).

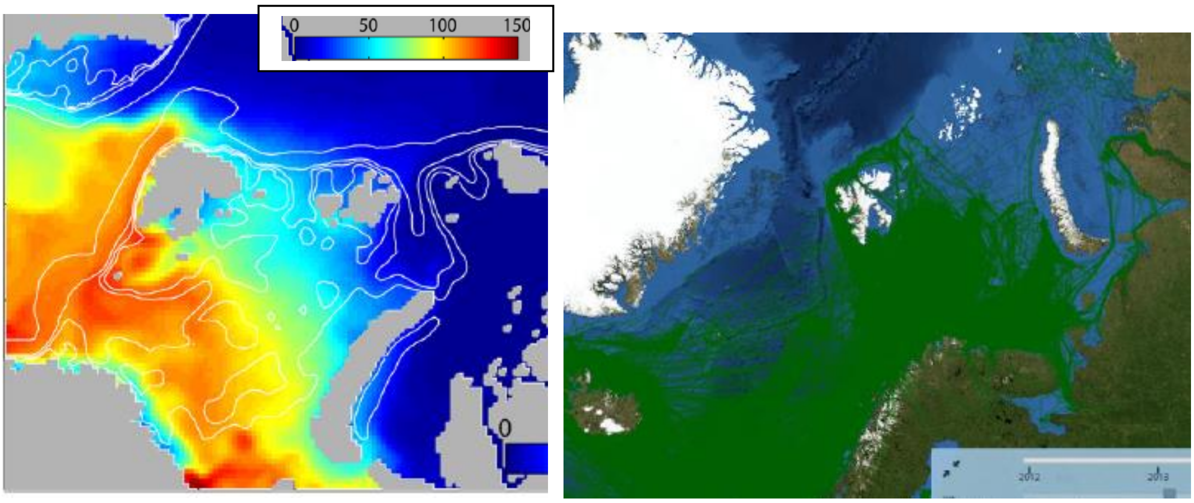


Figure 8 Left: Average (1995-2007) annual primary production (g C/m$^2$) in the European Arctic Seas (Reigstad et al. 2011). Right: Fishing vessels movements in the European Arctic Seas 2015 (Data provided by the Norwegian Oceanic Region Vessel Traffic Service (NOR VTS) in Vardø.

The productive waters off NW Svalbard are the northernmost high production areas in the world, and in a future Arctic Ocean, with generally lighter ice conditions, these waters may very well be at the centre of the preferred route for trans Arctic shipping, ref. Figure 2.

The three ecosystems presented hold several principal features of Arctic marine ecosystems in common: Low temperature adaptations, food chains based on lipid generation for energy storage and transfer to counteract the extreme annual abiotic variation, and adaptations to prolonged periods of darkness. The key role held by lipids in the marine ecosystem (Falk-Petersen et al. 1990) and the lipophilic nature of hydrocarbon compounds is a key contributor to the vulnerability of the Arctic marine ecosystem to discharges of oil (AMAP 1997; AMAP 2010; Hansen et al. 2011; Lee et al. 2011; Olsen et al. 2011).

## 4. Hydrocarbons in the marine ecosystem

Within shipping, and within exploration and exploitation of hydrocarbons (oil and gas), man-made discharges of oil to sea are the major area of concern. Most private and public post-incident contingencies and remedies are designed to handle oil spills (See paper I).

Hydrocarbons, organic molecules consisting of hydrogen and carbon atoms, are naturally occurring compounds, present in all ecosystems, food-stuff and organisms. Crude oil, generated from the decay of organic material over millions of years, and petroleum products distilled from crude (collectively referred to as petroleum) are made up of dozens of major hydrocarbon compounds and a wealth of rare compounds, in which nitrogen, oxygen and/or sulphur are incorporated into complex organic molecules. As crude oil is extracted, transported, distributed, or consumed, spills and unwanted releases may occur. In a recent review by Tornero and Hanke (2016), oil tanker accidents are summarised to account for 10-15% of all the oil that enters the global oceans, despite a decreasing trend in the frequency of extremely large accidental events (ref Figure 5).

Natural seepages of hydrocarbons from sub-seabed geological structures are frequent, and an important source of hydrocarbons in the sea (Wilson et al. 1974; Boitsov et al. 2011; Pampanin and Sydnes 2013). Natural hydrocarbon seeps were, in 2003, estimated to contribute 46% of the total petroleum hydrocarbons in the sea (NOAA 2016). Leaking or seepage of petroleum hydrocarbons from the seabed also occurs in the European Arctic Seas (Boitsov et al. 2011).

All crude oils are unique in composition, consisting of hundreds of different hydrocarbon molecules. Refined hydrocarbon products being transported or used as vessel fuel, are distilled and purified to specific standards, e.g. Marine Diesel Oil (MDO), gasoline, lubricants and heavy fuel oil (HFO) are fairly coherent in composition worldwide. In comparison to a blow out from an exploratory well, a shipping accident involving the loss of cargo or hydrocarbon propulsion fuel, will release a pre-known amount and composition of hydrocarbons to the environment.

Hydrocarbons are bio-degradable and will be exposed to photo-oxidation, physical weathering, spread, dissipation and biodegradation if spilled to sea (Fingas 2011). These processes will run at varying speed, depending on the available oxygen, sunlight and microorganisms (Lee et al. 2011). Discharges of oil, from ships, offshore operations or land based sources, are highlighted as threatening Arctic marine ecosystems by ACIA and OSPAR (Chapter 2.2.2). Coastal ecosystems and the MIZ are at risk of exposure if a slick of oil is drifting on the sea surface, and may be directly exposed in case of a ship grounding.

As a major driver for increased shipping into and within the Arctic, the petroleum industry has contributed to scientific research efforts, mostly by financing research on contingency, remediation and effects of oil in the marine environment. A recent, experimental contribution is the International Oil and Gas Producers Association (IOGP) programme "Arctic Oil Spill Response Technology – Joint Industry Programme" (Wiedmann et al. 2016), in which field experiments exposing plankton to oil were carried out in enclosures in the ice in the VanMijen Fjord (77°N, 16°E) in Svalbard (L. Camus and M. Frantzen, Akvaplan-niva, Tromsø pers. comm.). These results will be published in 2017. For an overview of impacts of oil spills on the marine environment, see recent reviews by Peterson et al. (2003), Lee et al. (2011) and Beyer et al. (2016).

Despite being natural compounds, experimental work has documented physiological damages in responses to oil exposure at many trophic levels. In the Arctic, early life stages of the fish lumpsucker (*Cyclopterus lumpus*), capelin (Frantzen et al. 2012, Frantzen et al. 2015) and polar cod (Nahrgang et al. 2016) are documented to be damaged by oil. The latter study identifying embryonal impacts to pelagic early life stages in exposure doses even at analytically undetectable levels.

In laboratory experiments, MDO has been shown to induce deleterious effects in boreal and Arctic pelagic copepods (*Calanus finmarchicus* and *C. glacialis*) (Hansen et al. 2013), while other experiments indicate limited, if any, differences in responses in Arctic benthic invertebrate communities and temperate counterparts when exposed to hydrocarbons (Olsen et al. 2011).

## 4.1 Polycyclic Aromatic Hydrocarbons.

Polycyclic Aromatic Hydrocarbons (PAH), are constituents of all types of both crude and refined oil. PAH are the collective name of a large group of compounds that contain two or more fused aromatic rings, such as the parent PAHs, the alkylated PAHs, substituted PAHs and PAH metabolites (Achten and Andersson 2015). PAH molecules are hydrophobic, persistent, carcinogenic and cause extensive disruption in cell functions in marine organisms upon exposure (Xue and Warshawsky 2005; Hylland 2006; Manzetti 2013).

PAH in the marine environment stem from combustion processes (pyrogenic PAH) and from spills and leakages of oil (petrogenic PAH) (Hylland 2006). PAH bio-accumulate in lipid storages (Meador et al. 1995). Accumulation occurs in marine organisms at all trophic levels and are influenced by a range of factors like environmental concentration, time and level of exposure. The organisms' ability to metabolise PAH compounds vary with trophic levels, being highest in vertebrates (Meador et al. 1995). PAH are generally partitioned to lipid-rich organs, while the metabolites can be found in most tissues, for example in fish bile (Aas et al. 1998; Nahrgang et al. 2010), which is the natural excretion route.

PAH often comprise around 10% of the organic compounds in crude oil (Tornero and Hanke 2016). Most have low solubility in water, thus in the marine environment they will sooner or later tend to be adsorbed to sinking particles and become deposited in the bottom sediment. Invertebrate filter feeders, such as blue mussel *Mytilus edulis*, are highly efficient accumulators and bio- concentrate PAH. Predators that prey on benthic animals (especially bivalve molluscs) can, through their diet, be exposed to relatively high concentrations of PAH from their prey organisms. This is further addressed in paper II and III.

PAH are decomposed in the liver of fish and other vertebrates, by processes involving the Cytochrome P450 enzyme system. In crustaceans, the hepatopancreas organ serves a similar function as the liver in vertebrates. Enzymes contribute in the replacing of hydrogen atoms with hydroxyl, oxygen or carboxyl groups in the hydrophobic PAH molecules. This increases the water solubility of the compounds, which are excreted as PAH metabolites through the bile. Monitoring of PAH metabolites in bile is a widely applied biomarker of PAH exposure in vertebrates (Aas et al. 2000; Hylland et al. 2006).

PAH occur naturally, and in some parts of the Arctic, particularly around Svalbard, marine sediments contain very high concentrations of PAH, often associated with coal in sub seabed structures (Dahle et al. 2006; 2009). Naturally occurring PAH are thus important to consider, when designing general monitoring programs, or when developing targeted post-spill monitoring. However, the bioavailability of PAH varies from compound to compound, and high environmental concentrations of PAH do not necessarily imply adverse biological effects (Deepthike et al. 2009).

# 5. Purpose, ethics and methods

My dissertation addresses impacts from current and future Arctic navigation, through a variety of approaches. In paper I, a plausible scenario for a single journey, based on vessel types, cargoes and navigation patterns of today, is described. This scenario provides a realistic set of impact factors to assess potential influences at an ecosystem level. Paper I was designed to provide a learning example of a cargo vessel, setting out on a well prepared voyage, planned according to today's procedures. The turn of events of the *Oleum* voyage, leading to wreckage, propulsion fuel and cargo loss is considered an unwanted, unlikely, but not impossible scenario for both current and future traffic. In developing the scenario, our findings on search and rescue (SAR), likely type and extent of environmental clean-up and remediation efforts to be initiated, and the impact assessment was included in our unfolding and final outcome of the scenario.

Based on input from the scenario, literature and *in-situ* Arctic data, a modelling exercise applying an Ecopath model (Polovina 1984; Christensen and Walters 2004), was performed. The model describes the energy flow through the shallow coastal ecosystem of the Pechora Sea. The Ecotracer module of this software was applied to assess ecosystem transfer of PAH, stemming from a near momentary loss of MDO (Paper II). A key issue to understanding Arctic ecosystems is that updated, geographically relevant data of sufficient temporal resolution are scarce. The modelling exercise was carried out to illustrate how a predictive model (Ecopath) can be applied in an area of poor data coverage.

The provision of new data highlighting extent and duration of an impact on Arctic species, and data contributing to the understanding of seasonality in distribution, abundance and sensitivity of Arctic marine food webs in general are key topics. My research includes the provision of new data through laboratory experiments. The accumulation and elimination of PAH in key species of a coastal Arctic ecosystem was investigated by exposure of the predatory red king crab, and two of its preferred prey species, the Icelandic scallop (*Chlamys islandica*) and the blue mussel to MDO (Paper III). After a week of exposure to low sulphur MDO, the experimental animals were allowed to recover for three weeks in clean water. This experimental setup was applied to mimic a discharge from a point source like a wrecked vessel, running on MDO. Understanding the impacts of PAH on Arctic ecosystems is essential, both for strategic planning and for reactive remediation of an unwanted event.

A major challenge to managing human activities in the Arctic is the scarcity of year-round relevant data on the distribution, abundance and activity of marine ecosystems. Increased summer navigation introduces no "new" risks, simply just adds to the established picture (with its intrinsic uncertainty). However, ice conditions are expected to lighten during autumn and early winter, opening up for increased navigation during the dark period. This may influence ecosystems in a poorly described state and sparsely supported by real time monitoring and data collection. Despite most of the *in-situ* knowledge on marine biological systems in the Arctic being based on data from the light period, recent investigations by Berge et al. (2015b) have documented high biological activity on several trophic levels, including zooplankton and benthos during the polar night. Paper IV, focusing on the polar night ecosystem conditions, is developed to amend the insufficient coverage of winter data. This scarcity of winter data was fully recognised when searching the literature for input information to paper II. The work was also carried out to provide further basis for challenging the notion that Arctic ecosystems are dormant during the polar night, and therefore less sensitive.

The final contribution of my research is the provision of knowledge of a poorly studied period of the Arctic year; the polar night. Paper IV describes winter feeding patterns and food overlap in coexisting gadoid fish of an Arctic winter habitat, obtained through field sampling (Paper IV).

Jointly my dissertation aims to throw light on the implications of Arctic shipping by combining theoretical problem formulation and contemplation, ecosystem modelling, laboratory experiments and field sampling and analyses.

## 5.1 Ethics and animal welfare

When initiating research, concerns for ethics, fairness, dissemination and animal and ecosystem welfare has to be included in the planning (Costello et al. 2016; NENT 2016). First of all, the question whether the planned research is needed and justifiable in terms of the associated costs, has to be answered.

Our current understanding of Arctic marine ecosystems is far from complete. Simultaneously, maritime transport is the most important way of transporting goods and commodities worldwide. More than 90 % of the world's trade is carried by sea (UN 2016). It is beyond doubt that shipping activities will increase in warmer, less ice-infested Arctic Seas. This makes any contribution to understanding impacts of Arctic shipping welcome. Based on the potential contribution to understanding Arctic marine ecosystems yielded by the research, I consider the expenditures in terms of effort, energy and animals sacrificed, as acceptable. All scientists and technical staff members having participated in the research have done so voluntarily and as part of their career and working life. No limitations have been enforced concerning freedom of speech and writing, and no gender specific selection of participants or roles in the work has been enforced.

Before initiating the experiments presented in paper III, the Norwegian Animal Research Authority had approved the setup and the use of test organisms (ID 5842). The number of animals exposed and sacrificed was kept at a minimum, and did not include any red-listed or rare species.

## 5.2 Application of methods

The current research has been conducted as table top exercises, collecting and treating already existing scientific data (paper I and II). Laboratory experiments were carried out in an approved animal experimental facility (paper III), and the empirical data for paper IV were collected using traditional marine biological field sampling equipment (trawl).

Demersal trawling, as applied in paper IV, is known to impact benthic habitats, biodiversity and production (Trush and Dayton 2002; Hiddink et al. 2006). Half of the trawl hauls providing data for paper IV were pelagic, not impacting the seabed, and the other half were demersal, causing some influence to benthic habitats in areas with limited prior trawling. During handling of the catches, standard *on board* procedures in marine biological sampling were followed, and no fish or invertebrates were unduly harassed. The trawling did not lead to any unwanted bycatch of mammals or seabirds. Field sampling was carried out as part of multi research project cruises, in which a number of research projects performed their sampling. Thus, the collective use of vessel resources reduced the environmental footprint of each individual project, compared to performing independent cruises.

## 5.3 Dissemination, uncertainty and precision in presented results

The National Norwegian Committee for Research Ethics in Science and Technology, NENT (2016) states (NENT 2016 Heading 8 (quote)): "Forskeren skal få fram den graden av sikkerhet og presisjon som kjennetegner forskningsresultatene" - "The researcher should clearly communicate what certainty and precision is connected to the research results." Paper I – III are published in acknowledged, peer-review scientific journals. Paper IV will also be published through this channel. This process contributes to ensure that guidelines for ethics and responsible scientific conduct are followed. Extracts of the results and conclusions drawn in the research, has been presented in newspaper chronicles and articles (in Norwegian), being subject to scrutiny by the newspaper editor. Two of the three published papers (paper I and III) are published as open access, to ease accessibility and make the results available to a broader audience.

The research methods applied in the individual papers, are all well established, but still contain intrinsic uncertainty. The search for and the development of a scenario depends on the amount and extent of information the authors are able to discover and gain access to. However, a scenario is not meant to be a detailed prediction, merely a sketch of a possible outcome of a chain of events. The research team behind paper I, (as well as paper II - IV) consist of skilled and experienced scientists, well qualified to design the *Oleum* scenario presented without adding undue personal bias.

Modelling is a simplification of the real world. Paper II is based on literature data available. In the Arctic, data of spatial, temporal and even thematically relevance for applying an Ecopath model are sparse. In an area of data scarcity, the "best available" dataset on a variable, is very often synonymous with "only available". This increases the risk of over-simplification, and reliance on outdated or insufficient data. Ecotracer is a relatively recent development of the Ecopath suite, and we were fortunate to have at hand reliable input values on the contaminants concentrations, from our own laboratory experiments (paper III) and from *in-situ* measurements of a real, winter MDO spill in Arctic Skjervøy (70.03°N; 20.97°E), Northern Norway (Sagerup and Geraudie 2014).

Based on the time and location of the *Oleum* incident, winter conditions and ecology of the circumpolar fish species, polar cod evolved to be a key issue of relevance to future Arctic shipping. Paper IV presents knowledge generated from *in-situ* collected material. Opposed to a literature survey, this material is collected in the field, analysed and assessed by the authors themselves, thereby not relying on fellow researcher's analyses and interpretations. The collection of samples by trawl includes uncertainty in performing the sampling, but this is considered a generic type of uncertainty, related to all scientific sampling applying trawling as method. All the trawl operations were performed by the crew of RV Helmer Hanssen (see front page illustration) from UiT, holding decades of experience from the European Arctic Seas.

# 6. Results

The research questions addressed are derived from a selection of the identified, generic impact factors related to shipping, pointed out in the prior chapters and summarised in Table 1.

## 6.1 Findings of paper I. What may happen?

Paper I presents a scenario with a diverse set of events that may take place in international shipping. Formulating a scenario, describing a chain of events leading to a specific outcome, is a frequently applied way of outlining potential future events. A scenario describes an option, one of many, dependent on the input data and the time perspective being looked at. Scenarios are typically applied to answer "what if?" questions, and may provide the basis for design of contingency, public development (e.g. oil spill contingency) and stakeholder actions.

The fictitious case of the vessel MV *Oleum* was designed to illustrate how a key type of vessel applied in today's traffic through the European Arctic may become wrecked, and the challenges associated with SAR, clean up and environmental impact (Figure 9). The study does not attempt to assess likelihood or frequency of the described chain of events. Whether the scenario is a worst case, a most likely case, or a dimensioning case for contingency planning, was not a key question in the present context. Vessel type, machinery, cargo and timing of the voyage was selected among the shipping operations being performed today (e.g. Figure 4B). Thereby we optimised representativeness for the type and scale of ecosystem perturbations, which the Arctic marine ecosystems may be exposed to. The choices made include:

- The vessel size (5000 dwt), type and machinery. MDO as propulsion fuel
- The wreckage location on a shallow rocky shore at 70°N
- The timing of the event to late October, late in today's navigation season
- The types and amounts of cargo, selected to represent the needs of ongoing and near future Arctic petroleum exploration activities

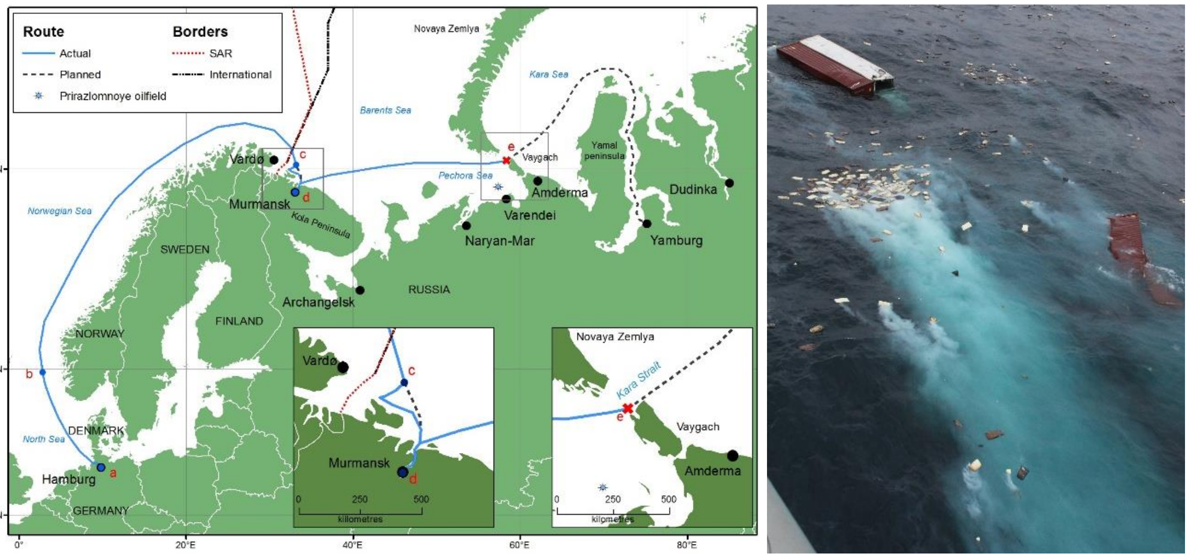


Figure 9 Left: The fictitiously planned voyage of *Oleum*, from Hamburg (Germany) to Yamburg (Russia). Right: Illustration of the fate of container kept cargo, from the wreckage of MV *Rena* off New Zealand, October 2011. Photo courtesy Maritime New Zealand. Further details in paper I.

We applied knowledge of today's technology and procedures for navigation in the final outcome of the scenario; rescue of the crew, but loss of vessel and cargo. During collection of input information, limitations in types and amounts of floating oil and debris that could be handled during an operation, were discovered and included in the description. The fact that container transported cargo is off limits to oil spill response crews and equipment is considered of key relevance in predicting spread and exposure of resources and habitats.

The design of a scenario is useful in at least two ways. The scrutiny and level of detail applied in search for input data (sources, accuracy, relevance, date, accessibility) governs the contents of the scenario and provides detailed insight in today's operational world. The way the endpoint of the scenario is handled in further analyses, defines the applicability of the findings for research and management. In our case, a near momentary, accidental release of MDO in late autumn was identified as one of the most conspicuous endpoints of the scenario. At the time of wreckage, *Oleum* had been travelling for eight days at economy speed. Her stores of propulsion fuel were at the time of wreckage down to approx. 140 tonnes of MDO. In addition, approx. 50 tonnes of diesel and lubricants were on-board the *Oleum*, in total approx. 190 tonnes of petroleum products. No emergency lightering was possible; the HC were all lost to sea.

Available input data on potential impacts of loss of the transported chemicals on-board *Oleum* were sparse, and the evaluation of potential impacts were hampered by commercial secrecy among cargo-owners. However, we fictitiously loaded *Oleum* with chemicals widely used in petroleum exploration, and regularly transported in bags stored in containers. We applied the Norwegian environmental classification code colours to the chemicals (Norwegian Activities regulation §63) based on the Harmonised Offshore Chemical Notification Format HOCNF (OSPAR 2010).

Designing a scenario includes performing a survey of current knowledge, and reporting the findings, not only in tables and text, but as contents and outcome of the scenario. The fictitious journey of the *Oleum*, based on experience from accidental events globally, indicates major challenges in Arctic navigation, SAR, oil spill response (OSR) and also points towards insufficiencies in our ability to predict the extent of environmental impacts of accidental discharges. Recovering container-transported cargo lost at sea is difficult under favourable climatic conditions; winter recovery operations in remote, poorly charted parts of the Arctic are considered close to impossible. In fact, no recovery options are available for chemicals or any other non-petroleum cargo released from rupturing containers at sea, and composition and ecotoxicological properties of container carried cargo are not readily available, and often kept as commercial secrets.

The type of propulsion fuel is routinely recorded by traffic surveillance systems, i.e. the amount and composition of propulsion fuel on-board *Oleum* was known to SAR managers and operators before the unfolding of the scenario – but the environmental implications of such a release need further research (Paper II).

## 6.2 Findings of paper II. Flow through the Ecosystem

Paper II addresses the trophic transfer of PAH through an Arctic marine ecosystem. Upon the fictitious grounding of *Oleum*, we tried to model the energy- and contaminant flow through the ecosystem hosting the wreckage. Most ecosystems of the Arctic are poorly mapped, and our understanding is at best based on relatively old data, often only available from the summer (light) period of the year. The latter fact is further addressed in paper IV.

In paper II, an Ecopath model is developed for the shallow Pechora Sea (67-71°N, 44-60°E, Figure 9), where the wreckage of *Oleum* took place. Bivalve mussels, mainly being predated by king eider (*Somateria spectabilis*) and walrus (*Odobenus rosmarus*), are key elements of the Pechora Sea ecosystem (Denisenko et al. 2003).

Based on literature, we managed to identify and provide input data for 27 functional trophic groups in the model (Figure 10), and we retrieved *in-situ* concentrations of PAH in water and blue mussels from a real MDO spill in Skjervøy harbour (Sagerup and Geraudie 2014). Finally, the experimental results on accumulation and excretion of PAH generated and presented in paper III, were applied as input to the modelling exercise.

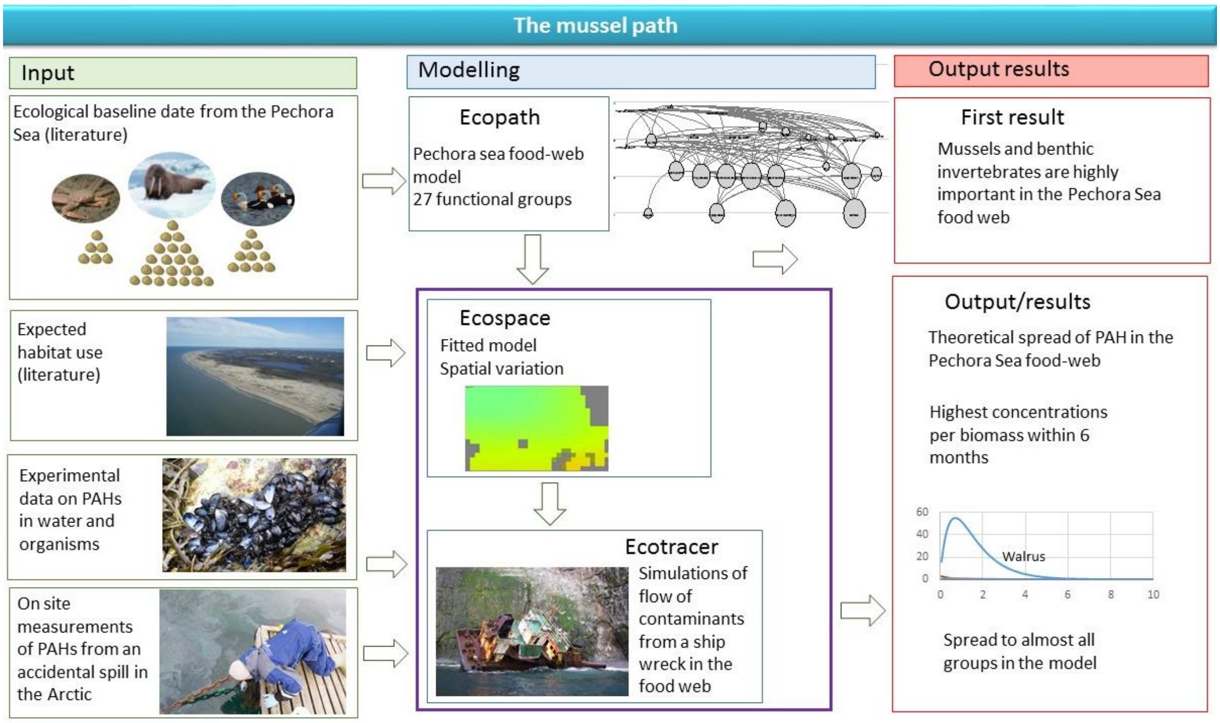


Figure 10 Conceptual presentation of the Ecopath model assembled for the Pechora Sea. For further details, refer to paper II. Photos courtesy Anita Evenset and Kjetil Sagerup, Akvaplan-niva.

The module Ecotracer was applied to get an estimate of absorption and propagation of PAH from the MDO discharge through the foodweb, and as such a measure of whether a case like the one at hand, can be expected to cause extended ecosystem perturbation. The modelling exercise revealed large challenges related to year round data availability. Ecotracer predicts spread of PAH to the top predators of the system within a very short timeframe, reaching maximum concentration values after a half to one year.

By varying the input values, we found that the lower trophic levels, dominated by bivalve molluscs and polychaetes (Dahle et al. 1995; Denisenko et al. 2003) responded fairly rapidly to the perturbation, and propagated the contaminants upwards in the food chains.

Ecopath, with Ecotracer as indicator of spread of a contaminant, does not provide input on the effects on the different trophic levels; e.g. from acute mortality to genotoxic long term effects and metabolic costs of activation of enzyme systems. But as a provider of input to what type of biomarkers in which organisms could be investigated to confirm exposure, and where to look for metabolites (species, areas, time) the exercise has been valuable.

## 6.3 Findings of paper III. Experimental exposure of invertebrate species to Marine Diesel Oil

The main topic addressed in paper III was the experimental generation of ecotoxicological response data for a key invertebrate species of an Arctic ecosystem. Release of a toxic component to the environment leads to effects on exposed individuals. The way an individual exposure is translated to population responses varies greatly in time and space and with the type, age and condition of the organism.

We exposed an Arctic predator, the red king crab, and two of its preferred prey species, the Icelandic scallop and blue mussels to MDO. This type of study addresses one step in the chain of events, potentially leading to a measurable environmental impact. The experimental organisms were exposed for one week at three concentrations (0, 7.4 and 19 mg/L MDO), and were allowed a post exposure recovery for three weeks in uncontaminated water (Figure 11). The experiment was carried out in the laboratory in Tromsø (69°N) at late autumn Arctic temperatures and light conditions (ref. the timing of *Oleum*'s fictitious voyage in paper I).

We exposed our animals to a commercially purchased MDO, in which the $\Sigma PAH_{16}$ made up 15% (Paper III; Electronic supplementary material). Both crabs, mussels and scallops showed significant and dose dependent increase of $\Sigma PAH_{16}$ in their tissues, and PAH accumulated in all animals at both exposure concentrations. The high exposure crabs reached four times the concentration of $\Sigma PAH_{16}$ in hepatopancreas compared to the low exposure group. Our observations indicated some degree of stress due to the MDO exposure, in the form of unrest, increased movement and escape response in the exposed crabs.

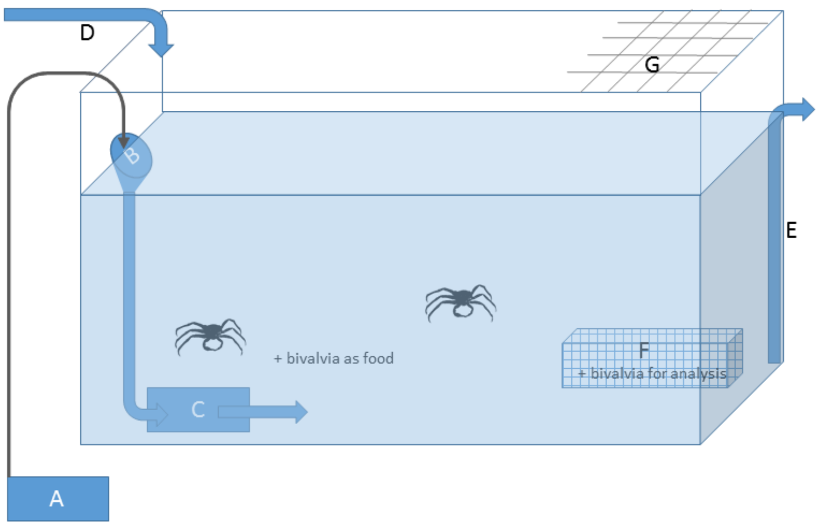


Figure 11 The experimental setup. A) Peristaltic pump supplying marine diesel oil (MDO). B) Funnel adjusted to drain top water layer and the supplied MDO to the circulation pump. C) Circulation pump with a capacity of 7.5 L/min. D) Inflow of natural seawater 1 L/min. E) Drainage outlet from bottom of the tank. A siphon secure stable water level in the tank. F) Cage for blue mussel (*Mytilus edulis*) and Icelandic scallop (*Chlamys islandica*) inaccessible to the red king crab (*Paralithodes camtschaticus*). G) Top cover net to avoid escape of the crabs.

Several biomarkers were measured in the crabs. An increase in glutathione peroxidase activity in high exposed crabs was observed after exposure, the catalase activity showed an insignificant increase with exposure, while no differences between groups were observed for lipid peroxidation and acetylcholinesterase activity. After transfer to clean conditions, the crabs excreted the $\Sigma PAH_{16}$. After three weeks of recovery in clean seawater, $\Sigma PAH_{16}$ concentrations in the crabs were significantly reduced, with no specific biomarker responses in exposed groups compared to the control, but the $\Sigma PAH_{16}$ concentrations in exposed crabs were still a factor 20 above the control group at the end of the recovery period. The results suggest that effects from instantaneous MDO spill only will have short-term effects on the red king crab.

Blue mussels and scallops also accumulated PAH in a dose response pattern; both species obtaining the highest soft tissue concentrations following the highest exposure, approximately double the values found in the low exposure groups (Paper III). The mussel sample collected prior to the exposure had non-detectable levels of PAH. We did not analyse any biomarker responses in the molluscs.

### 6.4 Findings of paper IV. Polar night ecosystem conditions

In a warmer global climate, boreal fish species are expected to expand northwards into a warmer Arctic domain. Encountering continuous darkness during the polar night, is potentially restricting feeding success in visually searching boreal fish, and may thus restrain their northward expansion. Locally occurring Arctic fish are hypothesised to be better adapted to feeding in the dark, but hitherto no investigations have documented the feeding and diet overlap in gadoid fish species during polar night.

In paper IV, we have analysed diet composition of the Arctic polar cod, potentially meeting competition from boreal Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) potentially penetrating northwards in a warmer Arctic. Data from five years (2012-2016) of mid- January trawling in the fjords of northwest Svalbard (78 - 81°N) are presented. The study documented the co-occurrence of the three gadoid species, and that the boreal gadoids fed as efficiently as their Arctic counterpart during the polar night. Polar cod had the highest frequency of empty stomachs.

Diet composition indicated opportunistic feeding, mostly on the most abundant prey species; e.g. krill (*Thysanoessa sp*.) and fish. During 2014-2016, a major switch in diet among all three species in Kongsfjord was noted (Figure 12). Polar cod and Atlantic cod changed from a krill dominated diet to fish, while haddock had a higher frequency of demersal prey groups like polychaetes. For all three species, prey items in advanced degrees of digestion were found in the stomachs, indicating feeding activity prior to each annual sampling.

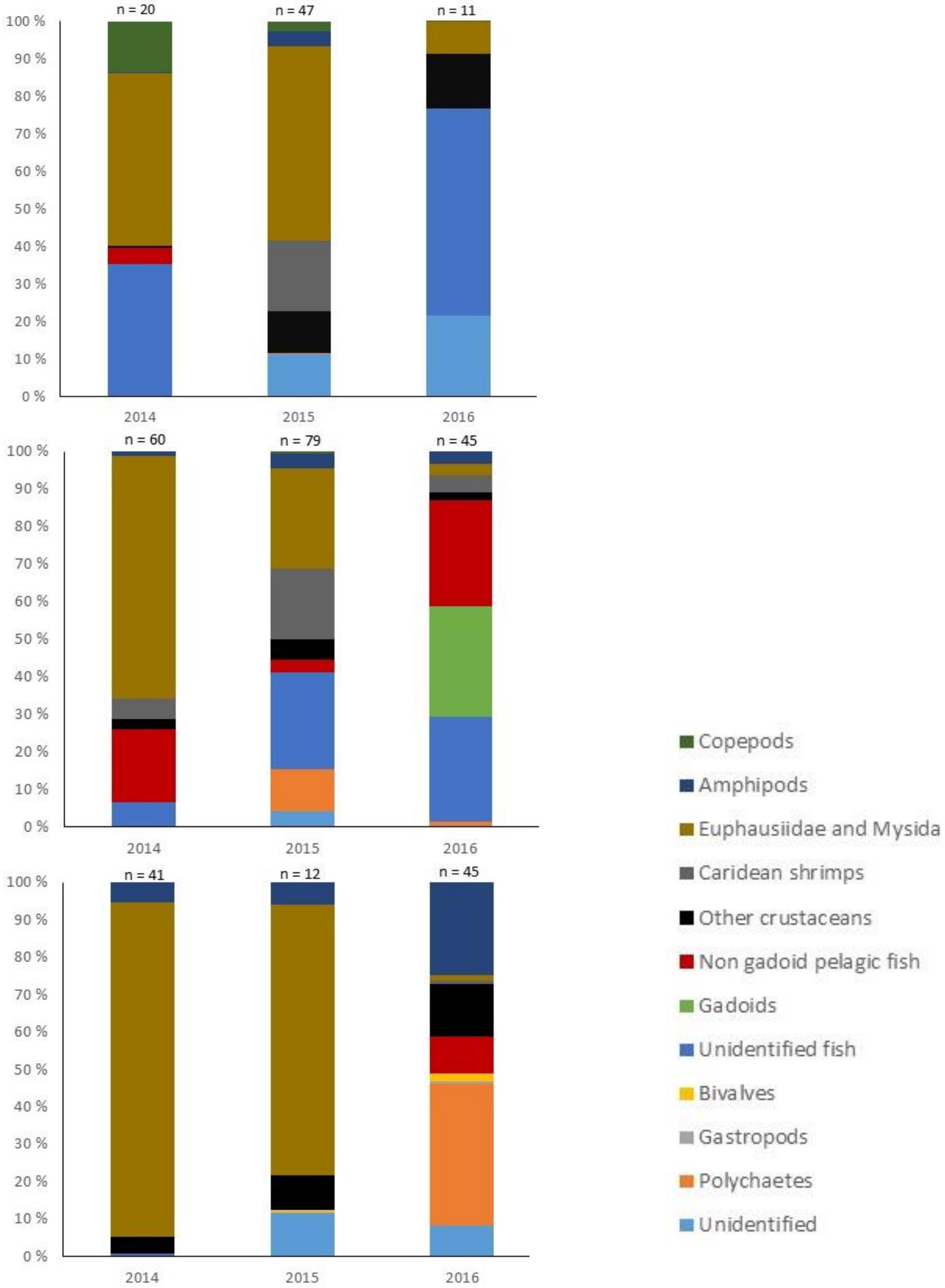


Figure 12 Diet composition (wet weight) of polar cod (top) Atlantic cod (middle) and haddock in Kongsfjord (Svalbard) 2014-2016. Fish < 25 cm TL.

The polar night does not seem to pose a limiting factor for Atlantic cod and haddock feeding (compared to the Arctic polar cod), meaning that their northward expansion in a warmer Arctic sea is unlikely to be limited by ability to detect and capture prey during polar night.

# 7. Discussion

## 7.1 The generic impacts of shipping

Shipping is a complex activity, as is Arctic marine biology. But what are actually the bio-environmental implications of current and future Arctic shipping? In Table 1, eighteen impact factors related to shipping were presented, and categorised under four main headings. My research has directly addressed one type of impact, the accidental release of cargo and propulsion fuel, and also, more indirectly, addressed the innocent passage[2] of a merchant vessel through an ice-free part of the European Arctic Seas.

Physical disturbances arise from innocent passages and the physical movement of a ship through the water. In ice infested waters, the circumpolar polar cod inhabits, among other habitats, crevices and hollows in the ice, to avoid predation from e.g. seals (Gradinger and Bluhm 2004; Hop and Gjøsæter 2013). The overturning of ice floes makes the polar cod accessible for avian predators (Divoky 1967), which may impact the population negatively. Noise and vibrations from vessels passing on-ice whelping areas for seals are hypothetically thought to alert and potentially scare the animals. The selection of nearshore leads, or the entrances to major river ports may cause frequent break-up of the ice, rendering migration routes for e.g. domestic caribou or roads for snowmobiles, inaccessible.

Polynya and leads are areas of open water during (major parts of) winter, and are as such attractive as navigation routes. Such areas are also essential to mammals, needing the open water to breathe. Navigation through polynya during darkness will increase the risk of collision with sluggish, slow moving Arctic whales, and is an issue identified by OSPAR and AMSA as topics needing further attention.

Soot, dust and black carbon (light absorbing carbonaceous substances) emitted as exhaust from ships traffic in the Arctic contribute to local ice melting. Most black carbon in the Arctic is modelled to arise from long transported emissions in Russia and South East Asia (AMAP 2015). Shipping contribute to carbon dioxide emissions. The global shipping industry contributes to the global warming, but is still the most efficient way of transporting large volumes e.g. compared to air, road and railway. Waste water and garbage dumped, either illegally or according to regulations, contribute to local eutrophication and littering.

During travel, vessels apply lubricants and hydraulic fluids to moving parts of their propulsion machinery. Operational discharges of oil and lubricants with cooling water may lead to smothering of birds, ice and mammals. It further provides low concentration toxic input to the marine foodweb. The operational discharges from ships include anti-fouling compounds. The former use of Tributyltin (TBT) has been abolished due to documented environmental impacts, and new, less toxic alternatives have been introduced.

Both shipping and infrastructure development has been shown to facilitate introduction and establishment of alien marine species (Katsanevakis et al. 2014). Many marine species travel naturally on the ocean currents, like blind passengers attached to other species (e.g. turtles, fish, whales), or they can travel as ongrowth on floating debris. However, species in a vessels' ballast

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[2] "Innocent passage" is a basic concept of the law of the sea, in which merchant vessels are allowed to pass any country's territorial waters as long as it is not prejudicial to the peace, good order or security of the coastal State. Such passage shall take place in conformity with UNCLOS and with other rules of international law. (http://www.un.org/Depts/los/convention_agreements/texts/unclos/part2.htm)

tanks, or as ongrowth on a ship's hull, will travel faster compared to spread by ocean currents alone. A ballast tank provides a stable environment during travel. The establishing of an alien species, transported to the European Arctic is identified as an event potentially of ecosystem scale impacts (ref Table 1).

In a review of the future of Arctic benthos (Renaud et al. 2015), the authors listed increased shipping as one of several influencing factors on distribution and abundance of benthic organisms. They speculate that influence is expected to be brought about as vessels are vectors for carrying individuals attached to hulls and/or in ballast water. The successful establishment of an alien species require that it finds tolerable living conditions at the new site, allowing completion of its entire life cycle. It is rather seldom that an introduced species finds conditions allowing for establishment, particularly when the destination offers very different abiotic conditions compared to departure location (Ware et al. 2016). The latter is the case with shipping to and from the Arctic, while across Arctic shipping is more likely to offer tolerable environmental conditions for a species from e.g. the north Pacific being transported to the north Atlantic.

The international ballast water convention was approved by IMO in 2004. By 2020 this convention requires purification systems for ballast water in all vessels, and the keeping of a ballast water account, documenting measures taken (e.g. changes of ballast water according to e.g. the Norwegian prescription or other nations legislation developed in line with the convention). The convention stipulated that it will enter into force one year after ratification by a minimum of 30 States, representing 35 percent of world merchant shipping tonnage. Finland's signing of the ballast water convention on 8$^{th}$ September 2016 was a milestone, as it brings the combined tonnage of contracting states to the treaty to 35.1441 percent, with 52 contracting parties, meaning that the convention will enter into force on 8$^{th}$ September 2017 (IMO 2016b).

Infrastructure supporting shipping includes updated sea charts, lighthouses, satellite surveillance and communications and SAR. The physical establishing of new routes, like the digging of the Suez and Panama Canals is also considered part of the shipping supporting infrastructure. Lighthouses and physical navigation aids cause local disturbance during their establishment and maintenance, however the Arctic has large areas still uncharted or poorly charted. Navigation in uncharted waters increase the risk of grounding and wreckage.

European Arctic shipping is dominated by destination traffic. Export of raw material and supply of commodities to island communities like Svalbard, Iceland, and Greenland depends on shipping. Current shipping lanes follows straight lines along the shortest routes between departure and destination, like routes from mainland Norway to Svalbard or from Murmansk to Siberia. Lighter sea ice conditions will hardly affect choice of routes, but will ease navigation during a larger part of the year. In terms of transit navigation frequency, the Arctic routes are still of marginal significance, e.g. even the peak year 2013 with a total of 71 NSR transit voyages, this equals less than two days' traffic through the Suez Canal that has an average of 45 ships per day (Suez Canal administration 2016).

Transit shipping will benefit from lighter ice conditions, providing shorter sailing distances between major industrial hubs of Europe and Asia. This is in itself a contribution to lower emissions to air.

A shipping accident releasing large amounts of propulsion fuel or hydrocarbon cargo to the sea is conspicuous, visible and causes impacts. We are able to predict some potential effects, derived from scenarios like our *Oleum* case. However, both factual and fictitious impacts become masked by the global climate change currently unfolding. The latter has a multitude of reasons, and it may turn out to be difficult to assess what processes are being influenced by shipping, and at what speed, compared to the general effects of climate warming.

## 7.2 The scenario – loss of diesel and cargo in the Arctic

Impacts to the marine environment following an oil spill are influenced by several factors; the amount and type of oil spilled, the location, the season and the presence of sensitive nature-types and resources (Kingston 2002; Boitsov et al. 2012). The smothering of the substrate (e.g. sediments, bedrock and ice) and individuals directly exposed to oil is, along with exposure to dissolved HC, the major ways of exposure. However, by letting *Oleum* run on a light (easily evaporable) propulsion fuel (MDO), the issue of smothering of birds' plumages or seals skin is less prominent in the present context.

Our scenario included a representative merchant vessel becoming wrecked. It is worth noting that the events putting marine pollution on the international agenda, all include oil spills several orders of magnitude larger than what we included in the *Oleum* case (ref. chapter 2.1). Our thoughts of developing the scenario around a merchant vessel instead of, for example a Very Large Crude Carrier (VLCC) or an ice strengthened 20 000 dwt shuttle tanker leaving the Prirazlomnoye oilfield in the Pechora Sea, was to highlight a mixture of environmental impacts, not a crude cargo loss alone. Given the magnitude of a potential discharge from a VLCC, such a scenario would have been just another, unlikely worst-case maximal crisis incident. Experiences from large oil-spills worldwide are plentiful (e.g. Kingston 2002; Beyer et al. 2016), however not from the Arctic, ref Chapter 2.1.

The *Oleum* story may provide many inputs to environmental assessments. Oil spill, ballast water tanks rupture, unmanageable containers astray, releases of chemicals stemming from the lost cargo etc. The *Oleum* was fiction but the discharge of 140 $m^3$ of MDO and approx. 50 $m^3$ of lubricants is likely the order of magnitude representative for incidents involving future cruise, - bulk, - or larger fishing vessels as well.

The main experiences gained in developing a scenario lies within the defining of overall framework, the search for and combination of technical information, and the endpoint of the chain of events. Despite shortcomings, the *Oleum* scenario as we let it end, postulated a moderate and overall short-lived environmental impact. This is in line with observations made after other, similar accidental spills in the Arctic (see below).

On 14 December 2013, Skjervøy harbour in Northern Norway (70.03°N; 20.97°E), was hit by an incident, leading to the spillage of 180 $m^3$ of MDO to sea from a fully loaded onshore storage tank (Sagerup and Geraudie 2014). This unique opportunity of comparing a postulated scenario (paper I) and recently completed ecotoxicological experiments (paper III) to a real event of the same character and environmental setting in the Arctic was truly unique. Our observations of blue mussel $\Sigma PAH_{16}$ concentrations in Skjervøy harbour showed a rapid reduction from 4466 µg/kg wet weight (ww) five days after the spill, to 1025 µg/kg ww after 27 days, and 730 µg/kg ww after 75 days. Two years (732 days) post spill, the blue mussels had values at background level (35 µg/kg ww) (K. Sagerup, Akvaplan-niva pers. comm).

Monitoring data on PAH in blue mussels after an Arctic MDO spill are rare, however, the speed of disappearance of the PAH from blue mussels in Skjervøy are comparable to what was recorded after the wreck of MV *Full City* in the Skagerrak (58.97°N; 9.70°E) in July 2009 running on HFO. Two thirds of the initially recorded $\Sigma PAH_{16}$ in oil exposed blue mussels had disappeared during the first 4 months after the spill, and another two thirds had disappeared after eight months, when conditions were evaluated as being back to pre-spill conditions (Boitsov et al. 2012).

Effects of two incidents involving leakage of diesel from storage tanks to the fjords around Svalbard has been documented through post spill investigations. In Svea (77.8°N; 16.6°E), 130 $m^3$ diesel ran out into the VanMijen fjord in 1978, while at Isfjord radio (78.06°N; 13.6°E) 100 $m^3$ diesel were spilled to the frozen ground and an unquantified amount of this entered the Isfjord in 2011. Both incidents were classified as "minor" and had "hardly detectable" impacts on the marine recipients (Schei et al. 1979; Gulliksen and Taasen 1982; Evenset 2012a, 2012b, 2015).

These results indicate that the Arctic marine environment, with its dominant species, is able to dilute, digest and decompose a diesel spill of the extent experienced in Svea, Isfjord and Skjervøy. However, in Svea only the presence of hydrocarbons in sediments were investigated, while in Skjervøy, the accumulation and excretion of HC from blue mussels were included in the post spill investigations. No high trophic level predators were included in monitoring of any of these incidents, as there were no reports or observations of oiled birds or mammals near any of the spills. Thus the monitoring after these incidents did not tell anything about transfer-effects up the food chain or direct physical exposure of top predators.

Yet another MDO spill in the European Arctic happened at Bjørnøya (74°34'N; 19°08'E) where the cargo vessel *Petrozavodsk* ran aground and became wrecked in May 2009. Post spill monitoring revealed PAH in glaucous gulls (*Larus hyperboreus*) blood up to 214 µg/kg ww one month after the spill (Strøm et al. 2011). Only gulls were included in this monitoring program, and one year after the spill, only 3 of 14 analysed birds had traces of PAH. For further discussion of these data, see Paper II.

Exposure, the contact between a discharged component and an individual organism, is a key word in the discussion of environmental impact of spilled oil. As mentioned previously, both polar cod and capelin have been documented to react negatively to experimental oil exposure, the former at unexpectedly low concentrations (Nahrgang et al. 2010; Nahrgang et al. 2016) (Chapter 4). Polar cod spawn in the Pechora Sea in winter (Gjøsæter 1995; Ajiad et al. 2011), while capelin is reported to occasionally spawn in the Pechora Sea (Gjøsæter et al. 2011 cit. Luka et al. 1991; authors personal observations 1992). Capelin spawn in spring- summer. Both species have large distribution areas, but the presence of spawning and young life stages of these key species both in summer and winter indicates challenges in applying temporal management actions, e.g. enforcing periods of no navigation, to reduce the chance of exposure of early life stages.

In a pilot scale, unpublished experiment, we tested one of the fictitious cargo compounds carried by *Oleum*, the water tracer chemical 2,4,5-Trifluorobenzoic acid, for acute toxicity to fertilized eggs of the sub-Arctic shallow water spawning lumpsucker (*Cyclopterus lumpus*). Fertilized eggs were exposed to six different concentrations (1 - 975 µg/ml) of 2,4,5-Trifluorobenzoic acid. In the highest concentration the buffer capacity of seawater was exceeded and the pH dropped to 3.1. In this treatment all eggs died within the first 24 hours. Even when removing the highest concentration, the hatching percentage gradually decreased with increased concentration of the acid. On a local scale, e.g. within metres of a discharge, buffer capacity of seawater is alleviating the drop in pH caused by release of an acid chemical. Local acute effects occur, but an insignificant contribution to ocean acidification is most likely the outcome.

*Oleum* grounded under ice-free conditions, but within weeks after the wreckage, ice started to form (Paper I). Based on the experiences from the wreckage of the container vessel *Rena*, just outside a sub-tropical major harbour in New Zealand (37°S; 176°E), where mobilization of heavy lift cranes and barges took nearly two months, no recovery of *Oleum* was anticipated until the following summer at the earliest. This may lead to repetitive releases of fuel and cargo as the wreck decays, as was seen after the *Petrozavodsk* incident at Bjørnøya (Strøm et al. 2011).

My research has not endeavoured directly into assessments of recovery and return to pre-incident conditions of the affected ecosystems. However, anticipating the presence of unaffected populations of affected species and the excretion times for HC found in blue mussels in Skjervøy and king crab in our experiments, the recovery from an *Oleum*-size incident in the Arctic seems to be within what is recorded from temperate areas (Boitsov et al. 2012; Kingston 2002).

### 7.3 The modelling exercise

When comparing the factors influencing the Arctic, like global climate change, long range transported contaminants, marine litter and petroleum exploration and exploitation, the experimental science becomes a valuable tool. Studies of tolerance and responses in cold-adapted species can be performed in laboratories, providing cost-effective contributions to individual responses and ecosystem understanding.

We were interested in using the scenario for looking at the ecosystem response and potential spread of PAH from MDO through the food chains, rather than predicting spread of the oil to provide input to oil spill combat. The Ecopath modelling tool is originally designed to evaluate manipulation of ecosystems, mainly by the removal of biomass through fisheries (Mackinson et al. 2009). It has also been applied in assessments as a tool for resource management in areas affected by a major oil spill, including Prince William Sound (60°N; 147°W), Alaska, host to the 1989 *Exxon Valdez* oil spill (Okey and Pauly 1999).

The modelled concentrations of transferred PAH seemed unrealistically high in some functional groups of our model, especially top predators. Providing data that can be used as input, from the same species or functional groups, prey types and pollutants was a major challenge. In addition, there are elements of physiological character and kinetics that are not taken into consideration in Ecotracer. Therefore, the constant adjustment for the removal (metabolisation) of PAHs within a functional group might have been too low, especially for the upper trophic levels. However, to be able to model the spread of pollutants at the ecosystem level, using many functional groups, simplification is also very important and Ecotracer proves to be a comprehensive and useful modelling tool.

One may argue that our scenario is not fully exploited in the sense that no combined effects of loss of propulsion fuel, extended duration of clean-up operations and loss of cargo are fed into the model simultaneously (only PAH and oil concentration data were included as a near momentary release). One can argue that applying dose-response theory, and letting a loaded oil-tanker ground, would most likely have identified measurable effects. But in a finer tuned search for an accident causing measurable and ecologically significant effects, our modelling exercise is adding value.

The king crab is an omnivorous predator (Jewett and Feder 1982; Mikkelsen 2013) deliberately introduced to the Barents Sea (Falk-Petersen et al. 2011; Oug et al. 2011). So is the presumably introduced snow crab (*Chionoecetes opilio*), having increased significantly in abundance in the central, deeper parts of the Barents Sea in recent years (Sundet and Bakanev 2014). We did not manage to find any literature data on PAH concentrations or metabolism in snow crab. Similarities between king crab and snow crab in ability to colonise and expand in a new habitat upon introduction indicate similarities in ecological niche. This again may justify our application of experimental results obtained on king crab, to also cover snow crab, thus assuming representativity for both shallow water and deep water crustacean groups in the model.

## 7.4 The laboratory experiments

MDO is currently a recommended hydrocarbon fuel over heavy fuel oil (HFO) in vessels operating in the Arctic (IMO 2016a). Our experiment indicates that impacts of a release of MDO to the marine ecosystems may be of a temporary nature for benthic marine species, such as the red king crab – but also that PAH is transferable to the top predators relatively fast. The red king crab was selected for the study due to its role as a highly priced fishery resource, and its prominent role in the Barents Sea ecosystem.

The experimental design and combination of exposure and recovery, was selected to mimic the evolving nature of the wreckage and concomitant spread and removal of HC from the environment. The complete recovery of PAH in the crabs within three weeks is rapid, and indicates the potential for a relatively rapid population recovery (given no lethal effects) following a discharge. However, experiences from the Arctic, e.g. the wreckage of M/V *Petrozavodsk* at Bjørnøya, is that although attempts are made to empty a wreck of its contents of hydrocarbons, it may thereafter be left to decay on the wreckage site due to economic or safety concerns. This may lead to repeated, low level leakage and exposure of local organisms to remains of hydrocarbons. Our experiments did not include repeated exposure, but that fact justify the choices made in the modelling exercise, i.e. no recovery of the wreck prior to first winter onset.

Repeated low level exposure to HC may lead to increased physiological expenditures in exposed individuals, due to metabolic costs of activation of detoxification enzyme systems and excretion of transformed (e.g. hydroxylated) compounds (Van der Oost et al. 2003; Beyer et al. 2010). Also, the exposure of life stages not occurring at the time of the initial wreckage and clean-up operation may occur when/if hydrocarbons leak over time. Leakage of oil over time from shipwrecks is an evolving issue worldwide, associated with the advancing decay of the many World War II shipwrecks, having been submerged for approx. 75 years (Faksness et al. 2015). This illustrates the longevity of the environmental impacts from leaving a wreck to "naturally decay".

Being an alien, invasive species in the Barents Sea, the Norwegian management practices implies that the red king crab should be kept at a low population level. However, due to its economic value, the crab is managed as a fisheries resource east of 26°E (North Cape), and as an unwanted invader in the waters west of this longitude. However, the crab is native to Arctic regions of the northern Pacific/Bering Sea, and the results of our experiments may likely be valid and useful for management outside the European Arctic. The low exposure concentration in the experiment (measured to 7.4 mg/L THC and 4.2 µg/L $\Sigma PAH_{16}$) is higher than what was observed in the water in Skjervøy harbour five days after the MDO spill (3.5 mg/L THC and 10.4 µg/L $\Sigma PAH_{16}$, Sagerup and Geraudie 2014). However, the comparison is valuable, and supports our experimental design and setup as valid and representative for a real Arctic MDO spill.

## 7.5 The polar night fish ecology investigations

Recent investigations have indicated that the Arctic marine ecosystems are far from dormant and inactive during the polar night. Berge et al. (2015b) documented biological activity in several ecosystem components of Svalbard waters during the polar night. Paper IV describes active feeding in coexisting gadoids, and the ability of both native polar cod and boreal Atlantic cod and haddock to detect and catch a wide selection of food items from both the pelagic and the benthic habitat in the dark.

The presence of highly digested remains of prey items in a large percentage of the stomachs of the three studied species indicated feeding over time in the polar night. This supports a general active feeding, and speaks against the possibility that the fish have just fed opportunistically at the mouth of the passing trawl, a phenomenon often observed in fisheries biology trawl sampling. We observed an interesting switch in diet among the three gadoids in Kongsfjord from 2014 to 2016; the krill were dominant in the diet of all three species in 2014 and 2015, but in 2016, krill had lost its importance, and the diet had changed in all three species, and also among species. Not only are the gadoids able to feed on a plentiful resource (krill, 2014) during the dark, they are also able to change to other prey categories.

In general, the marine Arctic fish fauna is only influenced marginally by ordinary shipping activities. Except of course fishing activity. Innocent passage of ships, even during polar night, are not expected to influence fish in any other way than navigation during the light season. The results of our winter fish investigations are documenting activity in one ecosystem component, the fish fauna. An active ecosystem during polar night may very well be similarly sensitivity to perturbations as the ecosystems during the light season, implying difficulties in applying temporally based management actions.

# 8. Conclusions and recommendations

Previous international assessment programs of shipping in the Arctic, like INSROP, have concluded that shipping in its itself, has limited if any impacts on Arctic ecosystems. The AMSA also largely points towards potential risks rather than documenting known effects on ecosystem processes and populations.

Management may govern the whereabouts of various types of ships and their cargo. For predictive purposes, that side of the equation is relatively easy to manipulate. However, the biological understanding and prediction of the year round environmental conditions in a warming Arctic poses far deeper challenges than just drawing a line on a map to delineate a no-go zone or no-go period for a specific type of vessel. Predictions of a seasonally ice free Arctic navigation route by mid-late 21$^{st}$ century makes summer navigation more attractive. However, late freeze up and the extension of the navigation season into autumn and winter, also makes navigation during polar night more likely.

Early life stages of most organisms at all trophic levels are individually most vulnerable to perturbations such as an oil spill. With increased polar night navigation, data on distribution and abundance of spawning products, and location of breeding areas is needed. Based on my research, the following conclusions are drawn

- A scenario approach provides a learning example by itself, and offers a wealth of opportunities for further analyses of potential outcomes of a chain of events, applicable in strategic planning.
- Spatial ecosystem modelling is a useful tool in remote areas with scarcity of updated environmental information. Application of *in-situ* and experimental data into the model strengthened the predictions of spread of contaminants to all trophic levels.
- Experimental ecotoxicology provides useful data on the accumulation and excretion of PAH in Arctic species. Design of experimental conditions are of outmost importance.
- Fish play an important role in a biologically active polar night ecosystem. Any perturbations may thus prove as environmentally significant during January as during July.

## 8.1 Further research options

Impacts of current activities are evaluated through monitoring; effects of future impacts are addressed through research. The research carried out in the wake of the *Oleum* scenario has addressed some key questions related to shipping in the Arctic. The scenario still holds many issues deserving attention and analyses to strengthen our understanding further.

I recommend increased focus on the addressing of the combined effects of a toxic cargo released simultaneously with MDO, and influencing the same ecosystem. This can be carried out through repeated modelling of low amounts of contaminants being released from a decaying wreck left on a specific grounding or wreckage site in the Arctic (given up on site due to access/financial issues). Long term effects, similar to the impacts found on herring following the Exxon Valdez accident in 1989 (Thorne and Thomas 2008) deserve attention also in a low-dose repeated exposure setting. The ecosystems of the European Arctic seas are within decades expected to be different from today. Changes are likely, and will be far more attributable to global warming than to shipping. General ecosystem understanding and feasibility of new technology (LNG or electricity as propulsion fuels) in a warmer Arctic deserve research efforts.

## 8.2 Management actions

Environmental management is enforced to avoid detrimental encounters between a man made impact factors (Table 1) and valuable or vulnerable environmental resources in space, time and/or order of magnitude of a perturbation. Mandatory shipping lanes in open sea for vessels carrying dangerous cargo (e.g. crude oil) are enforced in parts of the European Arctic Seas. This keeps dangerous cargo at some distance from the coast, providing more time to mobilise assistance from e.g. tugs. This measure keeps the impact factor separated from the coastal resources in space.

Despite the fact that we in paper II predict the spread of PAH through the foodweb, no obvious needs for mandatory shipping lanes for general cargo carriers in the European Arctic Seas seems needed per se. With Arctic climate warming at hand, both the concept of establishing marine protected areas (MPAs) and particular sensitive sea areas (PSSAs) need a re-evaluation as management measures, since species at several trophic levels are expected to experience large changes in distribution and abundance, like the northward expansion of gadoids touched up on in Paper IV.

For destination traffic, separation of impact factor and resource in space is not an option. That is the oil has to be extracted where the deposit is located, the ship has to call at an established harbour, and the tourists want to visit pre-defined sites. Regulations on timing of activities is thus an alternative option, but recent research, including paper IV, indicate that restrictions of seasonality in shipping becomes a less applicable management option, as the Arctic marine ecosystems are active both during the light season and during the polar night. And particularly in the Arctic, SAR and clean-up operations are expected to be long lasting, counteracting any measures taken to separate the impact factor from the ecosystem resource in time.

The IMO Polar code addresses technical design of ships, thus addressing the reduction of the order of magnitude caused by an unwanted event in the Arctic (and Antarctica). We have documented impacts of a MDO release, but not in an extent or order of magnitude questioning the recommendations of MDO over HFO in the Arctic. Translation of scientific results to management actions is brought about through the development of binding treaties supported by guidelines, recommendations and procedures. Through, among others, the AC, well established international structures exist, providing good platforms for enforcing science based management.

What if *Oleum* had sailed in 2030, under the rule of the Polar Code? – Most likely she would still have run on MDO (or potentially LNG). Ballast water would have been purified, but no measures against hull-ongrowth are included in the code. A future *Oleum* incident is likely to lead to discharge as described, in this respect the Polar code itself does not make an *Oleum* incident redundant or irrelevant.

Management of Arctic shipping, including the application of spatial regulations during specific periods of the year, the types of vessels and cargo being allowed, are needed. This can be achieved without jeopardizing the freedom of the high seas, and the right to innocent passages for merchant and passenger ships, as laid down in the 1982 United Nations Convention of the Law of the Seas (UNCLOS).

**"Navigare necesse erit"**

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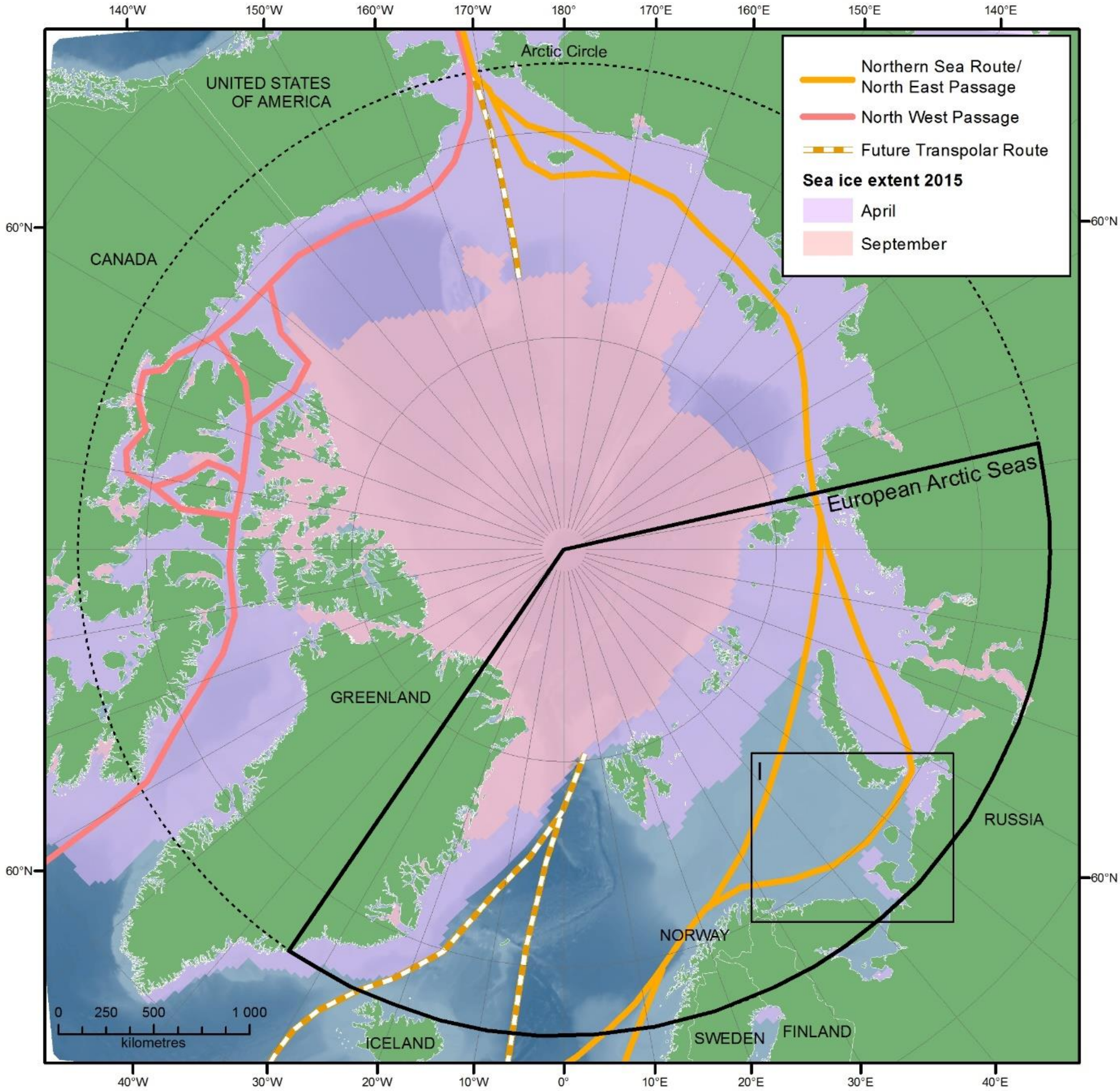
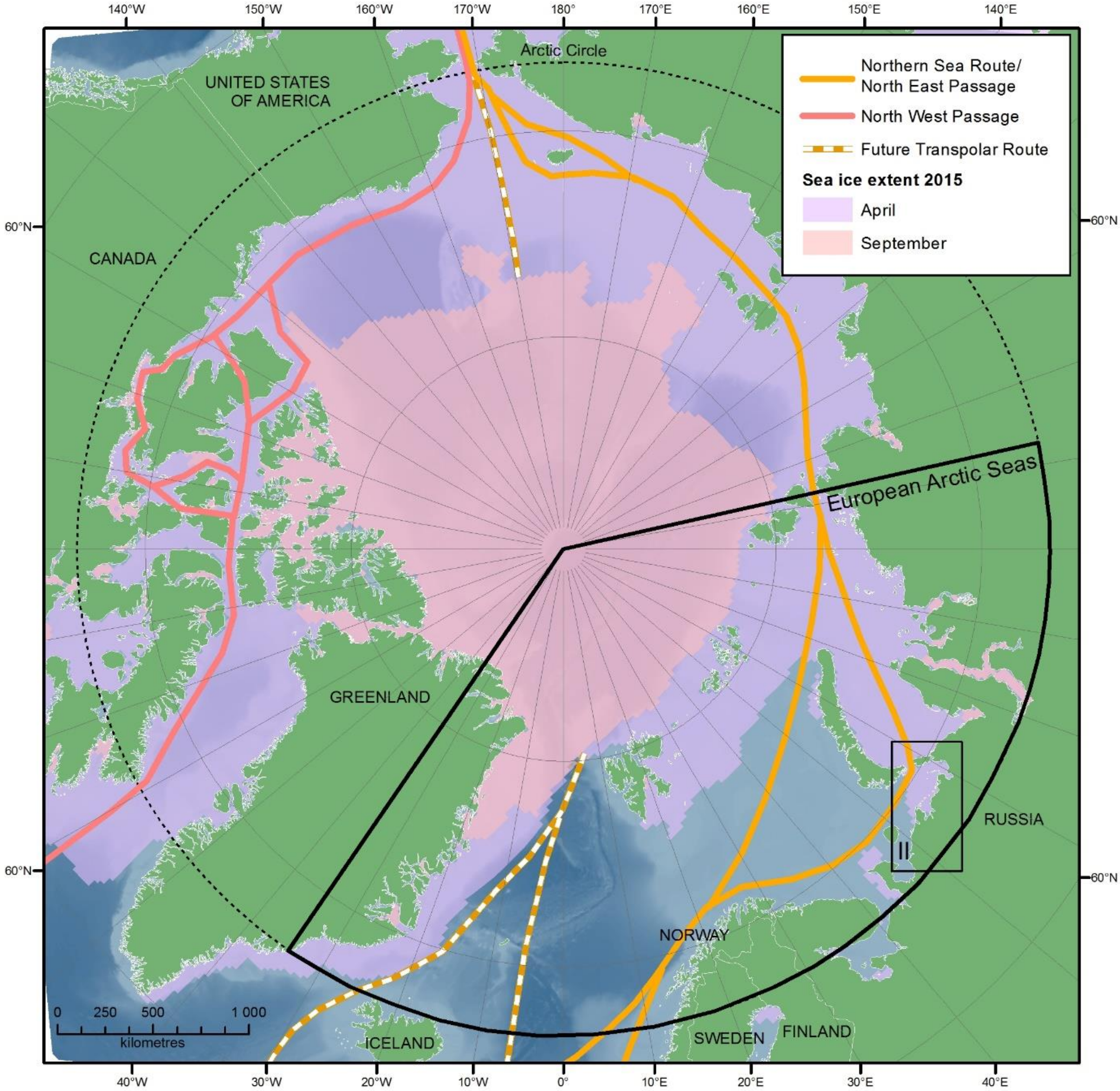
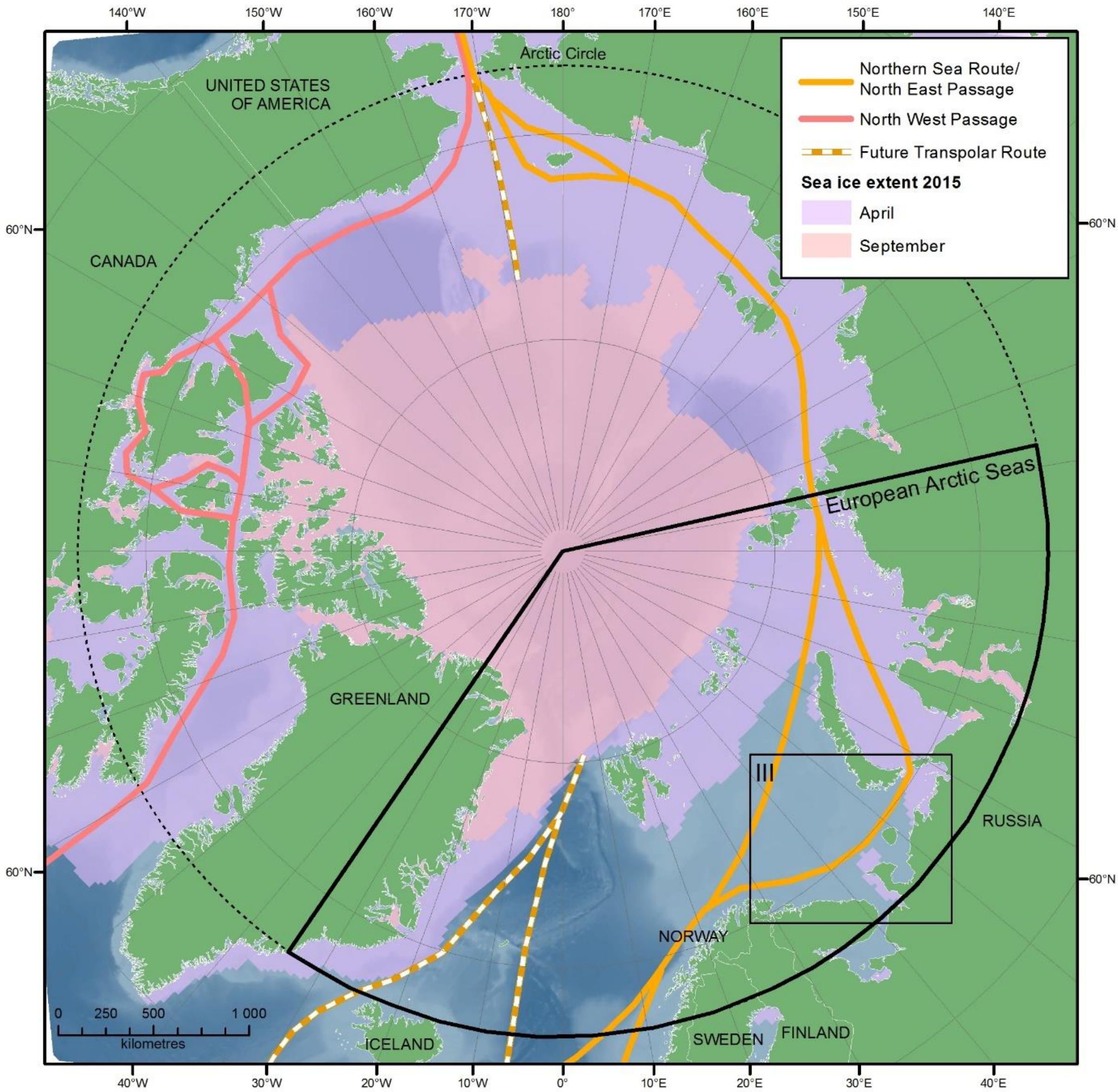
# The papers



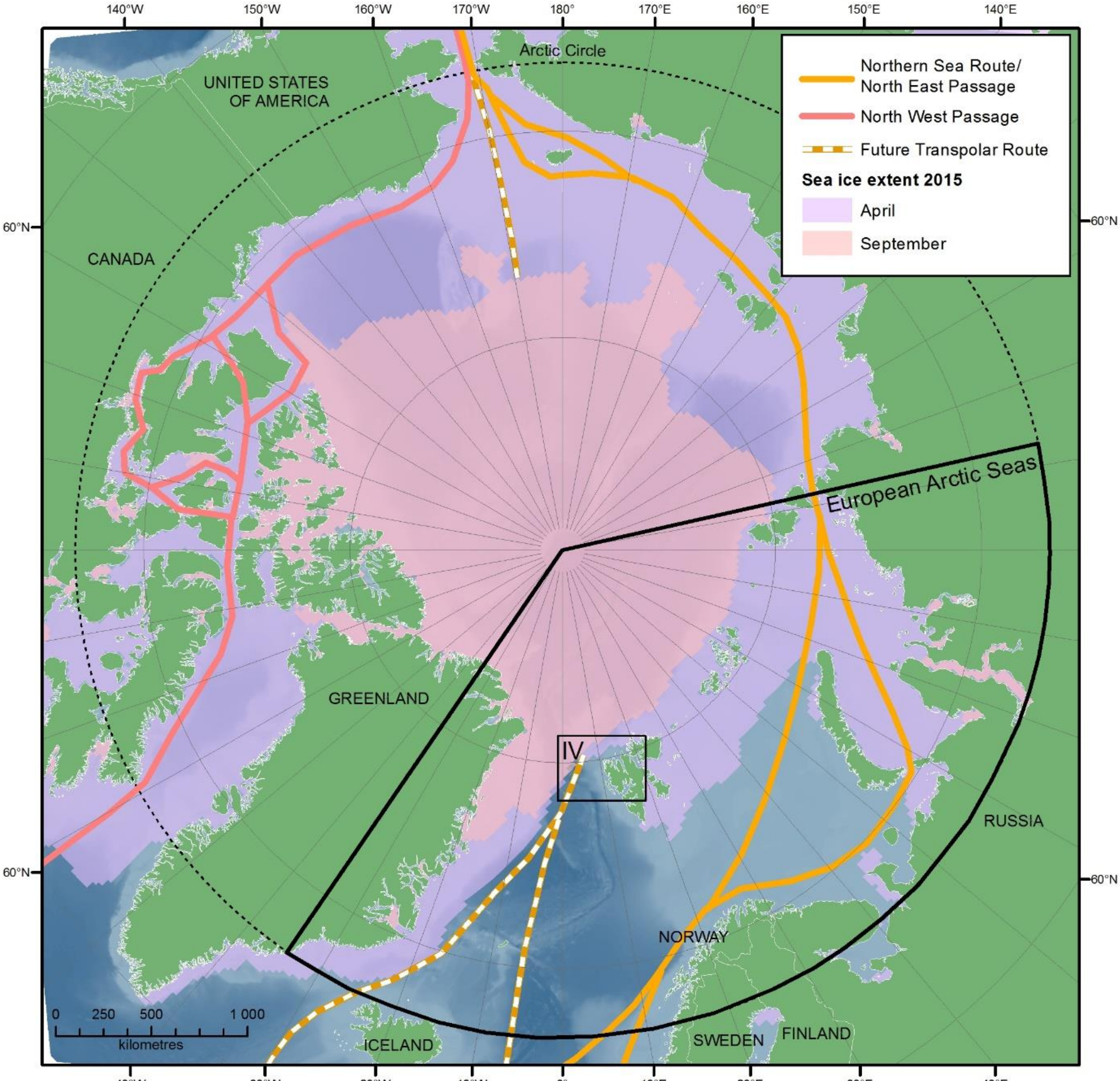

Paper I: Larsen L-H, Kvamstad-Lervold B, Sagerup K, Gribkovskaia V, Bambulyak A, Rautio R, Berg TE (2016) Technological and environmental challenges of Arctic shipping - A case study of a fictional voyage in the Arctic. Polar Research 35, 27977, http://dx.doi.org/10.3402/polar.v35.27977




Paper II: Larsen L-H, Sagerup K, Ramsvatn S (2016) The Mussel Path - Using the contaminant tracer, Ecotracer, in Ecopath to model the spread of pollutants in an Arctic marine food web. Ecological modelling 331:77-85. http://dx.doi.org/10.1016/j.ecolmodel.2015.10.011




Paper III: Sagerup K, Nahrgang J, Frantzen M, Larsen L-H. Geraudie, P (2016) Biological effects of marine diesel oil on red king crab (*Paralithodes camtschaticus*) assessed through a water- and foodborne exposure experiment. Marine Environmental Research 119:126-135. http://dx.doi.org/10.1016/j.marenvres.2016.05.027.




Paper IV: Larsen L-H, Cusa M, Eglund-Newby S, Berge J, Renaud PE, Falk-Petersen S, Varpe Ø In prep. Feeding activity and diet of gadoid fish in Svalbard waters during the polar night (Target journal Polar Biology).

## Co- authors statement

## Copyright approval (paper II)

# List of papers and contributions (co-author statements)

**Name of candidate: Lars-Henrik Larsen**

**Papers**

The following papers are included in my PhD thesis:

Paper I Larsen L-H, Kvamstad-Lervold B, Sagerup K, Gribkovskaia V, Bambulyak A, Rautio R, Berg T E (2016) Technological and environmental challenges of Arctic shipping - A case study of a fictional voyage in the Arctic. Polar Research 35, 27977, http://dx.doi.org/10.3402/polar.v35.27977.

Paper II Larsen L-H, Sagerup K, Ramsvatn S (2016) The Mussel Path - Using the contaminant tracer, Ecotracer, in Ecopath to model the spread of pollutants in an Arctic marine food web. Ecological modelling 331(2016)77-85. http://dx.doi.org/10.1016/j.ecolmodel.2015.10.011

Paper III Sagerup K, Nahrgang J, Frantzen M, Larsen L-H, Geraudie P (2016) Biological effects of marine diesel oil on red king crab (*Paralithodes camtschaticus*) assessed through a water- and foodborne exposure experiment. Marine Environmental Research 119(2016)126-135. http://dx.doi.org/10.1016/j.marenvres.2016.05.027.

Paper IV Larsen L-H, Cusa M, Eglund-Newby S, Berge J, Renaud PE, Falk-Petersen S, Varpe Ø (manuscript) Feeding activity and diet of three gadoid fish species in Svalbard waters during the polar night.

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**Contributions**

| | **Paper I** | **Paper II** | **Paper III** | **Paper IV** |
|---|---|---|---|---|
| Concept and idea | LHL, BKL, KSA, VGR | SIR, LHL | LHL, KSA, MFR | LHL, SEN, MCA |
| Study design and methods | LHL, KSA, RRA | SIR, LHL, KSA | KSA, MFR, PGE | LHL, MCA, SEN |
| Data gathering and interpretation | RRA, ABA, TEB, KSA, VGR | SIR, LHL, KSA | KSA, PGE | MCA, LHL, SEN |
| Manuscript preparation | LHL, KSA | LHL, SIR, KSA | KSA, JNA, MFR, LHL, PGE | LHL, MCA, JBE, PER, SFP, ØVA, SEN |

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