Arctic Shipping Emission in the Changing Climate

Vesa Vihannijoki
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Vesa Vihannijnjoki
Support for climate policy

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PREFACE

The report “Arctic Shipping in the Changing Climate” provides a review of issues relevant to shipping in the Arctic waters. It discusses the climatic changes occurring in the Arctic, and studies what consequences it might have on shipping emissions, among others black carbon.

The report was compiled as part of a project which supported the participation of Finnish experts and officials to the work on short-lived climate forcers within the Arctic Council and its working groups. The project provided focused and up-to-date information about issues like Arctic shipping (this report) as well as small scale wood combustion (as part of the ACAPWOOD project under the ACAP working group). The work was funded by the Ministry of Foreign Affairs, Finland via the IBA funding instrument.

Helsinki, March 2015

Kaarle Kupiainen
Senior research scientist, PhD
Finnish Environment Institute (SYKE)
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACIA</td>
<td>Arctic Climate Impact Assessment</td>
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<tr>
<td>AMSA</td>
<td>Arctic Marine Shipping Assessment</td>
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<tr>
<td>AO</td>
<td>Arctic Oscillation</td>
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<tr>
<td>BAU</td>
<td>Business As Usual</td>
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<tr>
<td>BC</td>
<td>Black Carbon</td>
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<tr>
<td>BLG</td>
<td>Bulk Liquids and Gases</td>
</tr>
<tr>
<td>CH₄</td>
<td>methane</td>
</tr>
<tr>
<td>CMIP5</td>
<td>Coupled Model Intercomparison Project Phase 5</td>
</tr>
<tr>
<td>CO₂</td>
<td>carbon dioxide</td>
</tr>
<tr>
<td>DAS</td>
<td>Double-Acting Ship</td>
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<tr>
<td>DEW</td>
<td>Distant Early Warning</td>
</tr>
<tr>
<td>DPF</td>
<td>Diesel Particulate Filter</td>
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<tr>
<td>DU</td>
<td>Dobson Unit</td>
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<tr>
<td>DWT</td>
<td>DeadWeight Tonnage</td>
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<tr>
<td>eBC</td>
<td>equivalent Black Carbon</td>
</tr>
<tr>
<td>EC</td>
<td>Elemental Carbon</td>
</tr>
<tr>
<td>ECA</td>
<td>Emission Control Area</td>
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<td>EEDI</td>
<td>Energy Efficiency Design Index</td>
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<tr>
<td>EEZ</td>
<td>Exclusive Economic Zone</td>
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<td>EF</td>
<td>Emission Factor</td>
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<td>EGS</td>
<td>Exhaust Gas Scrubber</td>
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<td>EPR</td>
<td>Eastern Polar Route</td>
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<tr>
<td>ESM</td>
<td>Earth System Models</td>
</tr>
<tr>
<td>FRISBEE</td>
<td>Framework of International Strategic Behaviour in Energy and Environment</td>
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<tr>
<td>FSICR</td>
<td>Finnish-Swedish Ice Class Rules</td>
</tr>
<tr>
<td>FWS</td>
<td>Fresh Water Scrubber</td>
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<tr>
<td>GHG</td>
<td>GreenHouse Gas</td>
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<tr>
<td>HFO</td>
<td>Heavy Fuel Oil</td>
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<tr>
<td>HiG</td>
<td>High Growth</td>
</tr>
<tr>
<td>IMarEST</td>
<td>Institute of Marine Engineering, Science and Technology</td>
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<tr>
<td>IMO</td>
<td>International Maritime Organization</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<tr>
<td>LAC</td>
<td>Light Absorbing Carbon</td>
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<tr>
<td>LNG</td>
<td>Liquefied Natural Gas</td>
</tr>
<tr>
<td>M</td>
<td>nautical mile</td>
</tr>
<tr>
<td>MARPOL</td>
<td>International Convention for the Prevention of Pollution from Ships</td>
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<tr>
<td>MFR</td>
<td>Maximum Feasible Reductions</td>
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<tr>
<td>MGO</td>
<td>Marine Gas Oil</td>
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<tr>
<td>MSD</td>
<td>Medium-Speed Diesel</td>
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<tr>
<td>μm</td>
<td>micrometer</td>
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<tr>
<td>N₂O</td>
<td>nitrous oxide</td>
</tr>
<tr>
<td>nm</td>
<td>nanometer</td>
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<tr>
<td>NMVOC</td>
<td>Non-Methane Volatile Organic Compound</td>
</tr>
<tr>
<td>NEP</td>
<td>NorthEastern Passage</td>
</tr>
<tr>
<td>NOₓ</td>
<td>nitrogen oxide</td>
</tr>
<tr>
<td>NSR</td>
<td>Northern Sea Route</td>
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<tr>
<td>NWP</td>
<td>NorthWestern Passage</td>
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<tr>
<td>O₃</td>
<td>ozone</td>
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<tr>
<td>OC</td>
<td>Organic Carbon</td>
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<tr>
<td>OPEC</td>
<td>Organization of the Petroleum Exporting Countries</td>
</tr>
<tr>
<td>OW</td>
<td>Open-Water</td>
</tr>
<tr>
<td>PC</td>
<td>Polar Class</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<td>--------------</td>
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<tr>
<td>PM</td>
<td>Particulate Matter</td>
</tr>
<tr>
<td>ppb</td>
<td>Parts-Per-Billion</td>
</tr>
<tr>
<td>pptv</td>
<td>Parts-Per-Trillion by Volume</td>
</tr>
<tr>
<td>rBC</td>
<td>refractory Black Carbon</td>
</tr>
<tr>
<td>RCP</td>
<td>Representative Concentration Pathway</td>
</tr>
<tr>
<td>RF</td>
<td>Radiative Forcing</td>
</tr>
<tr>
<td>SAR</td>
<td>Search And Rescue</td>
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<tr>
<td>SLCF</td>
<td>Short-Lived Climate Forcer</td>
</tr>
<tr>
<td>SLCP</td>
<td>Short-Lived Climate Pollutant</td>
</tr>
<tr>
<td>SO₂</td>
<td>sulfur dioxide</td>
</tr>
<tr>
<td>SO₃</td>
<td>sulfur oxide</td>
</tr>
<tr>
<td>SRES</td>
<td>Special Report on Emission Scenarios</td>
</tr>
<tr>
<td>SSD</td>
<td>Slow-Speed Diesel</td>
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<tr>
<td>SWIPA</td>
<td>Snow, Water, Ice and Permafrost in the Arctic</td>
</tr>
<tr>
<td>SWS</td>
<td>Sea Water Scrubber</td>
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<tr>
<td>TEU</td>
<td>Twenty-foot Equivalent Unit</td>
</tr>
<tr>
<td>UNEP</td>
<td>United Nations Environment Programme</td>
</tr>
<tr>
<td>WHO</td>
<td>World Health Organization</td>
</tr>
<tr>
<td>WiFE</td>
<td>Water in Fuel Emulsion</td>
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<tr>
<td>WPR</td>
<td>Western Polar Route</td>
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1. Arktinen ilmasto muuttuu—muutoksen nopeus arktisella alueella on globaalia keskiarvoa huomattavasti suurempi.

Lämpötilamittaukset osoittavat, että arktinen ilmasto on lämmennyt globaalia keskiarvoa nopeammin ainakin yli vuosisadan ajan. Tuoreemmat muutosnepoetut kuvaavat lukemat osoittavat, että ilmaston lämpeneminen on sekä kiihtynyt että paikallisesti eriytynyt. Toisin sanoen lämpeneminen on yleisesti ottaen nopeampaa, ja tämän lisäksi ero arktisen alueen ja globaalin keskiarvon välillä on kasvanut.


Periodisten ilmastovaihteluiden—kuten arktisen oskillaation (AO)—tiedetään vaikuttavan arktisen alueen lämpötiloinhin. Kuitenkin havaitut epäjohdonmukaisuudet arktisen oskillaation vaiheiden ja tosiasiassa mitattujen lämpötilojen välillä osoittavat, että viimeikaisia arktisen alueen lämpöennätyksiä ei voi selittää arktisen oskillaation avulla.

Myös pitkäaikaisempi luonnollisten periodisten vaihteluiden osuutta nyt havaitussa kehityksessä on arvioitu. Kaiken kaikkiaan on silti selvästä, että viimeikaisen kaltainen lämpeneminen tarkoittaa merkittävää muutosta huomattavan tasaisessa arktisessa lämpötilahistoriassa.

---

1 Arktisten lämpötilojen tilastohistoria on hyvin rajallinen; arktisen alueen muutoskeskiarvo on vuosien 1900 ja 2003 väliselle ajalle 0,09 °C vuosikymmenessä, kun taas vastaava globaali keskiarvo on 0,06 °C vuosikymmenessä.

2 Viimeiset neljäksi vuotta ajanajaksosta 1900—2003; muutosnepoetut tälle jakolle ovat 0,40 °C vuosikymmenessä arktisella alueella ja 0,25 °C vuosikymmenessä globalisti.

3 Noin 0,5 °C vuosikymmenessä.
Arktisen alueen poikkeuksellinen lämpeneminen tunnetaan yleisesti arktisena amplifikaationä. Arktisen amplifikaatio aiheutuu suurelta osin positiivisesta takaisinkytkennästä, joka liittyy lämpötilan nousun sekä sulavan lumi- ja jääpeitteen väliseen vuorovaikutukseen.


Joskus myös polaarinen amplifikaatio. Arktinen amplifikaatio on kuitenkin täsmällisempi ilmaus, sillä vastaavaa ilmiötä toisella polaari- eli napa-alueella (Antarktiksella) ei ole havaittu.
Käynnissä olevat arktista merijäätyä koskevat muutokset ovat moniulotteisia:

- Jääpeitteen kokonaislaajuus ja kokonaispinta-ala vähenevät.
- Jääpeitteestä tulee keskimäärin nuorempaa ja ohuempaa.
- Jääpeitteen vuosittainen kesto lyhenee.

Tämänkaltaisen kehityksen seurauksena jäättömän Jäämeren toteutuminen näyttää olevan lähempänä kuin koskaan ihmisen historiassa.

Muita arktisen ilmastonmuutoksen aiheuttamia vaikutuksia arktiselle merenkululle ovat muutokset säätensä ja merisäässä sekä poikkeamat jäättökäytännön ja ahtojään käyttäytymisessä. Yleisesti ottaen muutama keskeinen sääilmiö määrittää arktisen merenkulun erityisoluisuutetut; näitä ovat kylmä (jäättömien ja jäättymien), *nuoo näkyyys* (käsäsumut ja pöllövä lumi) ja *nopeasti kehittyvä* arktinen syntyperity *meri* (polaarimatalat eli arktiset pyörremeryrskyt). Arkinen ilmastonmuutos vaikuttaa osaltaan näiden ilmiöiden yleisyteen ja voimakkuuteen.


Merenkulukouluosuhteet on muuttuaan viime vuosina, sillä jäättömän merijään tarkoittaa tilannetta, jossa arktisen merijääpeitteen kokonaislaajuus on alle miljoona neljän kilometriä vähintään viiden peräkkäisen vuoden ajan.

Muutokset arktisessa jäättökäytännössä johtavat myös jään erilaiseen koostumukseen ja täten jään poikkeukselliseen käyttäytymiseen. Vanha ja paksu jää sulaa nykyisellään nopeammin kuin verrattain ohut yksivuotinen jää, minkä seurauksena *nuoren jään suhtelinen osuus kasvaa ja jään keski-ikä laskee* (ks. Taulukko A). Nuorempia jääpeitteitä on haurampaa ja alttiimpaa ulkoisille iskuille, kun taas vanhaa jääa on vaarallisempaa aluksille.

### 3. Odotettavissa olevat muutokset arktisen merenkulun olosuhteissa


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Yleisesti ottaen arktisen ilmaston lämpeneminen johtaa jään rakenteen murtumiseen, mikä kasvattaa uusien pienten jäävuorten lukumäärää huomattavasti. Jäävuoret aiheuttavat erityisesti lisääntyneen kesäsumun kanssa merkittävän uhan turvalliselle merelliselle operoinnille.

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4. Arktisen merijään vetäytyminen ja sen seurauksena tapahtuva arktisen vesialueen avautuminen johtaa ihmisperäisen toiminnan määrän lisääntymiseen arktisella alueella.

Huolimatta arktisen ilmastonmuutoksen laivaliikenteelle aiheuttamista haasteista on selvää, että arktisen jääpeitteen vetäytyminen seurauksena arktisen alueen merijää peitteen vetäytyminen aiheuttaa merkittävän uhan avautumiselle arktisella alueella. Merijääpeitteen laajuus ja pinta-ala sekä merijääpeitteen laajuus että merijääpeitteen pinta-ala kuvaavat merin pinnalla olevan jään määrää—sä. merenpinnan jäätyneiden ja sulien osien suhteellisia osuuksia—mutta niitä käsitellään typillisesti erillään. Merijääpeitteen laajuus vetii niiden osa-alueiden summaan, joissa jääpitoisuus on vähintään 15 %, kun taas merijääpeitteen pinta-ala on jonkin tietyn osa-alueen pinta-alan ja sitä vastaavan jääpitoisuuden tulo. Toisin sanoen merijääpeitteen laajuus tarkoittaa aluetta, jossa ylipäänsä esiintyy hyödyllistä laajennustyypiltä erillään.

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Tällä tavoin määriteltynä merijääpeitteen laajuudella on erityinen merkitys monivuotisen hengen kasvattamisessa ja sen vaikutuksessa kevyesti tai ollenkaan jäättä vastaan vahvasti aluksille.

4. Arktisen merijään vetäytyminen ja sen seurauksena tapahtuva arktisen vesialueen avautuminen johtaa ihmisperäisen toiminnan määrän lisääntymiseen arktisella alueella.


Tärkeimmät transarktilaiset liikennöintimahdollisuudet liittyvät Atlantin valtameren ja Tyynen valtameren välisii oikoreittein, joko Pohjois-Amerikan (Luoteisväylä, Northwestern Passage eli NWP) tai Venäjän (Koillisväylä, Northeastern Passage eli NEP) tai joskus myös Pohjoismerien merite, Northern Sea Route

Transarktiset reitit voivat olla jopa 50 % lyhyempiä perinteisiin meriteihin verrattuna. Matkan pituuden lyheneminen tarkoittaa vähentynyttä polttoaineen kulutusta ja täten myös pienempää päästöjen määrää, mikä kokonaisuudessaan saattaa tehdä transarktisesta liikennöinnista taloudellisesti houkuttelevaa. Matkan pituuden lyheneminen ei kuitenkaan suoraan tarkoita vastaavaa matka-aikaa, sillä transarktisissa oikoreitteissä saattaa sisältyä tekijöitä, jotka vaikeuttavat matkantekoa huomattavasti. Esimerkiksi merijään olemassaolon vuoksi matkantie on lyhyempi ja lisäksi etenemiseen tarvitaan suurempaa lähtötehoa.

Koko transarktisen liikennöinnin täytyy olla sekä teknisesti että taloudellisesti perusteltua, ja vain tällä tavalla voidaan realistisesti arvioida oikoreitteihin liittyviä kehitysmahdollisuuksia. Tarkasteltaessa transarktisen liikennöinnin toteutuskelpoisuutta on otettava lukuisia tekijöitä huomioon. Näitä tekijöitä ovat matkan pituus ja matka-aike (aluksen nopeus), matka-aikana (läpikulkuaikaan) liittyvä luotettavuus, mahdollisten jäättömien olosuhteiden kesto ja vaihtelut, polttoaineen hinta ja maa-ilman kehitys, mahdollinen jäämuutoksen ja läpikulkukumaksut, kalustoinvestoinnit ja henkilöstön kouluttaminen, turvallisuus, sekä riskien hallinta ja vakuutusmaksut.


Arktisen alueen sisäisen liikenteen uudet mahdollisuudet liittyvät ennen kaikkea luonnonvarojen saavutettavuuden paranemiseen. Arktisessa öljyn ja kaasun saavutettavuuden paranemiseksi voisi olla huomattava strategista merkitystä, sillä jopa viidennesen maailman maailman kartottamattomista öljy- ja kaasuvareista on arvioitu sijaitsevan arktisella alueella.

Arktisen alueen öljyn ja kaasun tuotantoa koskevat arviot ovat kuitenkin hyvin vaihtelevia, sillä arktiset olosuhteet asettavat huomattavia haasteita oletettujen reservien tehokkaalle ja turvalliselle hyödyntämiseen. Taloudelliset seikat hidastavat arktista toimintaa niin ikään; arktisten reservien hyödyntäminen on toistaiseksi ollut varsin kallis verrattuna suotuisampien toimintaympäristöjen kustannustasoan.

Toisaalta öljyyn ja kaasun liittyvän liikennön strategista merkitystä, sillä jopa viidennesen maailman kartoittamattomista öljy- ja kaasuvareista on arvioitu sijaitsevan arktisella alueella.

Arktiselle alueelle toimivien liikennöitsijöiden varuste- ja valmiustaso on vaihteleva, mikä puolestaan on yhteydessä hyvin vaihtelevaan arktiselle alueelle toimivien liikennöitsijöiden tehostettua ja turvallisuutta. Tämän käsitteen yhteydessä arktiselle alueelle liittyvän liikenteen uudet mahdollisuudet voivat olla merkittäviä.}

5. Arktisella alueella toimivien liikennöitsijöiden varuste- ja valmiustaso on vaihteleva, mikä yhteydessä puutteellisten rannikkoinfrastruktuurin kanssa aiheuttaa huomattavia epävarmuutta operoinnin turvallisuuden suhteen.

Yleisesti ottaen operoinnin sääntely arktisella alueella on vähäistä ja riittämätöntä. Lisäksi varustetun ja valmistelun puutteellisuus voivat vaikuttaa operointiin yhdessä paljon negatiivisesti.

- **Ei ole takeita siitä, että arktisella alueella operoiva alus asettuu arvokseen turvallisuuteen**. Arktisissa on paljon meri- ja jääpältä, mikäli alus on turvattomina oloillaan. Arktisessa on hyvin vaihdettavaa, joka voi vaikuttaa reservien tehokkaalle ja turvalliselle hyödyntämiseen.

- **Arktisella alueella operointi vaatii miehistölää paljon**. Arktisella alueella on vaihdellavaa, mikäli arktisessa on hyvin vaihdettavaa. Arktisella alueella on vaihdellavaa, mikäli arktisella alueella on hyvin vaihdettavaa.

- **Kunnollisen rannikkoinfrastruktuurin puuttuminen vaikuttaa huomattavasti erilaisten tapaturmien edellyttämää määrätietoja ja nuoella toimintaa arktisella alueella.** Arktisella alueella on vaihdellavaa, mikäli arktisella alueella on hyvin vaihdettavaa.

6. Humanitaarisen ja ympäristöllisen katastrofin tilastollinen riski nousee merkittävästi ennustetun arktisen merenkulun määrän lisääntymisen vuoksi.

Muun merenkulun ohella myös arktisen turismin olennaisena osana kasvavan operoinnin kaikista merkittävimpien estojen poistuessa. Kuitenkaan monet arktisella alueella liikkuvat matkustaja-aluset eivät välttämättä ole jäättäviä vastaan asianmukaisesti huomattavasti, kun arktisessa on hyvin vaihdellavaa. Arktisella alueella on vaihdellavaa, mikäli arktisella alueella on hyvin vaihdettavaa.

- **Pitkät etäisyydet ja meri- ja jääpältä liikenne jättää arktisella alueella arkkitehtuurin valmiudeksi.** Arktisella alueella on vaihdellavaa, mikäli arktisella alueella on hyvin vaihdettavaa.

- **Arktisella alueella on vaihdellavaa, mikäli arktisella alueella on hyvin vaihdettavaa.** Arktisella alueella on vaihdellavaa, mikäli arktisella alueella on hyvin vaihdettavaa.
Arktinen ympäristö on kokonaisuudessaan muodostunut kausittaisen ja säännöllisesti toistuvien luonnollisten äärimmäisyyksien ehdolla, ja sen kyky sopeutua äkillisiin muutoksiin on heikko. Näistä osatekijöistä johtuen myös sellainen onnettomuus, jossa vuotaneen aineen määrä on suhteellisen vähäinen, voi arktisella alueella lopulta johtaa huomattavaan ekologiseen katastrofiin.

7. Arktisen alueen lisääntyneestä laivaliikenteestä aiheutuvilla päästöillä voi olla huomattavia ja ennakoinnottomia haittaa vaikutuksia erityisen herkälle arktiselle ympäristölle.


Arktinen alue on syrjäisyydestään ja heikosta saavutettavuudestaan johtuen sääliynyt verrattain koskettomattomana, minkä vuoksi arktisen alueen nykyiset päästötasot ovat hyvin alhaisia verrattuna globaalillehin keskiarvoihin. Tämänkaltaisessa ympäristössä jo absoluuttisesti arvioituun pienet liisikset päästömaarista voivat tarkoittaa merkittävää suhteellista lisääntymistä. Tämän vuoksi myös arktisen laivaliikenteen kasvu voi potentialisesti saada aikaan huomattavia muutoksia arktisen alueen paikallisissa pitoisuuksissa.

Arktisen ympäristön ainutlaatuisuus monimutkaistaa merkittävästi arktisen alueen kehityksen hallintaa ja kontrollointia. Koska arktista ympäristöä ja sen käyttäytymistä ei ole voitu havainnoida kovin kattavasti, lisääntyneiden päästömaärillä lopullisia vaikutuksia arktisella alueella on vaikeuta tai lähes mahdotonta ennakoaa. Erityisesti suuren mittakokoisen vuorovaikutukset jäättävät ja ilmaston välillä sekä moninaiset takaisinkytentämechanismit asettavat lisähaasteita Arktisen tulevaisuuden ennustamiselle.
8. Tietyillä paikallisesti vaikuttavilla ilmansaastepäästöillä—kuten mustalla hiilellä—on ilmastonmuutoksen kannalta erityistä merkitystä juuri lumi- ja jääpeitteillä alueilla pohjoisilla leveysasteilla.

Tietyt ilmansaastepäästöt ovat verrattain lyhytyökkäisiä, minkä seurauksena ne eivät sekoitu täydellisesti ilmakehässä ja niiden ilmastolliset vaikutukset ovat luonteeltaan paikallisia. Näin ollen lyhytkäisten ilmansaastepäästöjen maantieteellisellä sijainnilla on erityistä merkitystä.


9. Arktisella alueella tapahtuvien musta hiili -päästöjen lisääntyntä määrä voi edistää arktista ilmastonmuutosta merkittävästi.


Absorboitunut lämpö nostaa pinnan lämpötilaa ja saa aikaan ilmakehän lämmenemistä yleisellä tasolla, mikä puolestaan edesauttaa lumen ja merijään sulamista. Edelleen kun lumi- ja jääpeite vetäytyy, yhä enemmän suhteellisen tehokkaasti lämpösäteilyä absorboivaa pintaa altistuu auringon säteilylle.

Tämänkaltaiset positiiviset takaisinkytkennät ovat arktisen ilmastonmuutoksen kannalta äärimmäisen keskeisiä. Tarpeeksi pitkälle kehittyneitä positiivisia takaisinkytkentöjä voi olla hyvin vaikeata pysäyttää tai edes hidastaa, sillä ne jatkuvasti vahvistavat itseään. Yhteen vetäen voidaan todeta, että juuri positiiviset takaisinkytkennät määrittävät arktisen alueen kehityksen yleisen suunnan.


Tästä syystä muutokset arktisella alueella tapahtuvien musta hiili-päästöjen määrässä ovat ilmastonmuutoksen näkökulmasta arvioltaan hyvin merkityksellisiä. Arktisen alueen syrjäisyystä johtuen myös arktisen laivaliikenteen lisääntymisestä näkötä etenkin myös arktisen alueen muutuksia aiheutuvaa musta hiili-päästöasemaa, siis vaikka arktisen laivaliikenteen absoluuttinen määrä pysyisi hinnattuna, arktisen alueen musta hiili-pitoisuus kasvaa huomattavasti arctisen alueen liikenteen kasvattuessa.

10. Arktisesta laivaliikenteestä aiheutuvien musta hiili-päästöjen määrä ja merkitystä on arvioitava sekä päästöasemien nykyisyyttä että tulevaisuutta silmällä pitäen.

Jotta olisi mahdollista arvioidaa lisääntyneestä arktisesta laivaliikenteestä aiheutuvien musta hiili-päästöjen potetiaalista vaikutusta, on ollut tarpeellista arvioida nykyisenkaltaisesta laivaliikenteestä aiheutuvien musta hiili-päästöjen määrä ja merkitystä arktisen alueen musta hiili-pitoisuus. Myös päästöä seurauvia—säteilypakkoteen ilmaistavia—ilmastoavikutuksia on laskettu.
Ennusteiden välinen huomattava suuruusluokka ero johtuu ennen kaikkea erilaisista lähtökohtaoletuksista koskien arkisen alueen laivaliikenteen kasvua. Hillitymmät arviot perustuvat niin sanottuihin Business-As-Usual kehityskulkuihin arkisen laivaliikenteen kasvun osalta, kun taas korkeampien arvioiden taustalla on oletus arkisen laivaliikenteen tasaisen merkittävästä kasvusta.

Oletus arkisen laivaliikenteen huomattavan kasvun mahdollisuudesta puolestaan perustuu lisäarvoetuksiin arkisen liikennöinnin toteutuskykyisyydestä. Näin ollen implisiittiset oletukset arkisen merijään ja arktisen alueen yleisten merenkulkuolosuhteiden tulevasta kehityksestä ovat oleellista tekijöitä arvioitessa päästöennusteiden mielekkyyttä ja toteutumisen mahdollisuutta.


Musta hiili -kerrostumien suhteen tutkimustulokset ovat kahtalaisia. Toisaalta lisääntyneen arkisen laivaliikenteen vaikutukset globaaliin tai edes arkisen alueen keskiarvoon voivat hyvin pieniä tai jopa olemattomia, mutta toisaalta paikallisen tasojen vaikutukset ovat kiistattomia.

Browsen ja kumppaneiden (2013) mukaan arkisen laivaliikenteen päästöjen osuus arkisen alueen keskiarvosta on pieni, vaikka arkisen laivaliikenteen määrän oletettaisiin kasvavan korkeimmalla esitetyn ennusteenIV mukaisesti: vain 0,7 % arkisen alueen musta hiili -kerrostumista olisi peräisin arktisesta laivaliikenteestä (vuonna 2050). Toisaalta paikalliset vaikutukset ovat ennuste mukaan paljon merkittävimpää, joja 15 % Grönlannin länsirannikolla ja Beringinmerellä.

Wintherin ja kumppaneiden (2014) tulokset ovat samankaltaisia, vaikka taustaoletuksena on huomattavasti hillitympiiIV kasvu. Tutkimuksen mukaan lisääntyneen arkisen laivaliikenteen aiheuttamat päästöt johtaisivat 1,0 %:n osuuteen musta hiili -kerrostumien arkisen alueen keskiarvosta kesällä 2050. Paikalliset vaikutukset ovat jälleen kerran suurempia, ja merialueella Grönlannin itäpuolella sekä kaikista korkeimmilla leveyspiireillä arkisen laivaliikenteen päästöjen osuus olisi noin 5 %.

11. Kansainvälinen merenkulkujärjestö on toiminut aktiivisesti sekä globaalista että arktisesta laivaliikenteestä aiheutuvien päästöjen vähenemiseksi.

Kansainvälinen merenkulkujärjestö (International Maritime Organization, IMO) on jatkuvasti etsinyt keinoja merenkulusta aiheutuvien päästöjen vähenemiseksi. Sekä maailmanlaajuisesti että paikallisesti vaikuttavia toimenpiteitä on tutkittu ja pantu täytäntöön. Toimenpiteiden kohdistaminen jollekin tietylle alueelle tai jollekin tietylle alusten luokalle on keino, jolla on tarkoitus saavuttaa merkittäviä tuloksia kohtuullisin kustannuksin ja haittavaikutuksin.


Mustan hiilen kohdalla on ollut muutamia perustavaa muutosi kysymyksiä, jotka ovat estäneet säännösten laatimisen ja täytäntöönpanon sekä täten päästövähennyksit. Ennen kaikkea mustan hiilen yritysliitteen määrittely on osoittautunut huomattavasti tehtävääksikä, sillä musta hiili ei koostu mistään yhtätkä yksittäiseltä eri alkuaineiden tai yhdisteiden kombinaatioista. Mahdollisuus suorittaa mustan hiilen liittyviä mittauksia sekä tarkasti että kustannustehokkaasti on ollut keskeisessä roolissa mustan hiilen määritelmän kehitettäessä.

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III 118 % kasvu vuodesta 2012 vuoteen 2050 (1,58 tuhannesta tonnista 3,45 tuhanteen tonniin).
IV Erittäin huomattava kasvu 0,88 tuhannesta tonnista (vuonna 2004) 16,7 tuhanteen tonniin (vuonna 2050).
VIII 118 % kasvu vuodesta 2012 vuoteen 2050 (1,58 tuhannesta tonnista 3,45 tuhanteen tonniin).
Vaikka määritelmän pragmaatisesta luonteenkaan käytännönläheisyystä—ollaankin yhtä mieltä, IMOn jäsenvaltioiden väliset erimielisyydet sovellettavien mittausteknologioiden suhteen ovat hidasta-neet päästövähennysprosessia kokonaisuutena. IMO:n jäsenvaltiot ovat yleisesti ottaen samaa mieltä siitä, että ainakin alustava määritelmä voi olla puhtaasti tekniin eikä täten tiukan tieteellinen, mutta hyväksyttyjen mittausteknologioiden lopullinen valinta on muodostunut ongelmaksi.

IMO on myös mukana musta hiili -päästöjen vähennysteknologiaa käsittelevässä tutkimustyössä. Arvioitaessa vähennysteknologioiden monta tekijää on otettava huomioon, kuten esimerkiksi mahdolliset vaikutukset muihin päästölajeihin ja teknologioiden kaupallinen saatavuus sekä oletettu käyttöönotoai-ka. Yleisesti ottaen tehokkain vaihtoehto koostuu lopulta monesta yksittäisestä päästöjä vähentävästä osaratkaisusta.

IMO:n musta hiili -työhön liittyvän päästövähennysteknologiavertailun perusteella seuraavat seitsemän vaihtoehtoa sisältävät kaikista eniten potentiaalia musta hiili -päästöjen vähentämiseen liittyen:

- EEDI (Energy Efficiency Design Index, energiatehokkuuden suunnitteluniidexi)
- Matkanopeuden alentaminen ja moottorien uudelleensäätö (Slow steaming)
- Vesi—polttoaine-emulsio (Water in Fuel Emulsion, WiFE)
- Raskaan polttoöljyn jatkokäsittely (Heavy Fuel Oil distillate)
- Nesteytetty maakaasu (Liquefied Natural Gas, LNG)
- Hiukkassuodattimet diesel-moottoreihin (Diesel Particulate Filters, DPF)
- Pakokaasupesurit (Exhaust Gas Scrubbers, EGS)

Taulukko B koostaa eri vaihtoehtoihin sisältyvät päästövähennyspotentiaalit mustan hiilen ja hiilidioksidin osalta sekä muita vaihtoehtoihin liittyviä teknisiä reunaehtoja.
12. Ilmansaastepäästöistä aiheutuvat terveys- ja ympäristöongelmat eivät suoraan liity ilmastollisiin mekanismeihin ja ilmastonmuutokseen.

Vaikka monilla ilmansaastepäästöillä on vaikutuksia sekä ilmaston että ihmisten terveyteen ja ympäristön hyvinvointiin, näiden vaikutusten taustalla toimivat mekanismit ovat yleisesti ottaen erilliset. Nämä ollen eri vaikutusten käsittely voi olla perusteltua tehdä toisistaan erillään, kuitenkin niin ettei ilmasto- vaikutuksia korostamalla kuitenkaan saada aikaan huomattavia terveys- ja ympäristövahinkoja tai toisin päin.

On tärkeää huomata, että samalla määrällä ilmansaastepäästöjä voi olla vähäisiä tai jopa olemattomia ilmastovaikutuksia mutta silti huomattavia haittavaikutuksia ihmisten terveydelle ja ympäristön hyvinvointiin. Toisin sanoen vaikka jonkin ilmansaastepäästömäärän ilmasto- vaikutuksista voitaisiin voitaisiin käydä kriittistä debattia, tästä huolimatta päästövähennyksillä voidaan saavuttaa huomattavia muita ympäristöllisiä ja terveydellisiä etuja.

Mustan hiilen kohdalla viesti on varsin selvä: vaikka useiden tutkimusten mukaisesti lisääntyneen arktisen laivaliikenteen aiheuttamat musta hiili-päästöt pysyisivät kohtuullisella tasolla, päästövähennyksillä voi silti olla merkittäviä positiivisia vaikutuksia.


13. Hiilidioksidipäästöjen rooli pitkän tähtäimen ilmastotavoitteiden saavuttamisessa on keskeinen, mutta musta hiili –päästöllä ja -päästövähennyksillä voi silti olla huomattava merkitys erityisesti kaikista haavoittuvimpien alueiden ilmastonmuutoksessa.

Vaikka mustan hiilen ilmasto- vaikutukset ovat maailmanlaajuisessa mittakaavassa kiistatta merkittäviä, hiilidioksidipäästöjen keskeistä roolia ei tule vähätellä tai sivuuttaa. Hiilidioksidin on kaikista tärkein yksittäinen kasvihuonekaasu, ja juuri hiilidioksidipäästöistä aiheutuu 55—60 % ihmisperäisestä säteilypakotteesta.

Lisäksi mustan hiilen ja hiilidioksidin elinajassa on merkittävä ero. Musta hiili on niin sanottu lyhytikäinen ilmasto- vaikutin (Short-Lived Climate Forcer, SLCF) tai lyhytkäinen ilmansaaste (Short-Lived Climate Pollutant, SLCP), koska sen elinaika ilmehässä on suhteellisen lyhyt juuri hiilidioksidien verrattuna. Mustan hiilen elinaika on muutamasta päivästä viikkoihin, kun taas hiilidioksidin vaikuttaa ilmehässä vuosituhansien ajan.

EXECUTIVE SUMMARY

1. The Arctic climate is changing, and the rate of change in the Arctic is notably faster compared to the global average.

Historical temperature record indicates that the Arctic climate has been warming faster than the global average for at least over a century of time. When examining more recent rates of global and Arctic warming, it becomes clear that the warming of the climate has both accelerated and spatially differentiated; that is, the climate is warming faster in general, and the difference between the Arctic and the global average has increased.

Since 1980 the increase in average temperature in the Arctic has been twice the global rate, and the surface air temperatures measured in the Arctic since 2005 have been higher than for any five-year period ever recorded (see Fig. A). Local changes in the average temperature are even more drastic than the Arctic averages.

The changes do not spread evenly over the year, but they are centered seasonally. Warming is greatest in autumn and early winter and less significant over the rest of the year. Over the Arctic Ocean, temperatures over the past ten years have been over 4 °C warmer in autumn and winter compared to the average for 1951—2000. No greater increase of temperature was observed at any time of year anywhere else on Earth.

Periodical climate patterns—such as the Arctic Oscillation—that for their part affect the Arctic are known to exist, but the inconsistencies between the phases of the Arctic Oscillation and observed temperatures imply that the recent record-high Arctic temperatures cannot be explained by the Arctic Oscillation.

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Fig. A. Observed changes in temperatures relative to the 1961—1990 mean at land-based weather stations in the Arctic. Source: AMAP 2011b.

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\[1\] The Arctic rate has been 0.09 °C per decade over the period 1900 to 2003, compared to the global average of 0.06 °C per decade.

\[2\] Corresponding rates for the last forty years of the time period in question (1900—2003) are 0.40 °C per decade and 0.25 °C per decade, respectively.

\[3\] Approximately 0.5 °C per decade.
Also the existence of possible long-term natural patterns and their manifestation in recent trends has been considered, but the recent rates of warming yet represent a substantial change in the unusual stability of Arctic temperatures.

The exceptionally high rate of warming in the Arctic is generally known as Arctic amplification. In the core of Arctic amplification is the positive feedback mechanism which the interaction of rising temperature and the melting snow and sea ice constitutes.

2. The Arctic climate change will alter the general conditions for Arctic marine activities remarkably in the 21st century.

The retreat of Arctic sea ice cover defines the development of shipping conditions in the Arctic during the 21st century. The retreat of sea ice results from the Arctic climate change and its development (see Fig. B). On the other hand, due to the positive feedback mechanism, the retreat of sea ice also contributes to the Arctic climate change notably. The future of Arctic marine activities depends crucially on the development of the Arctic climate and cryosphere. However, the development of Arctic marine activities may also have significant effects on the Arctic climate.

![Figure B](image.png)

Fig. B. February and September CMIP5 multi-model mean sea ice concentrations in Northern Hemisphere for the periods (a) 1986—2005, (b) 2081—2100 under RCP4.5, and (c) 2081—2100 under RCP8.5. The pink lines indicate the observed 15% sea ice concentration limits averaged over 1986—2005. Adapted from: IPCC 2013.

The ongoing changes in the Arctic sea ice cover are manifold:
- The total ice extent and area are decreasing.
The ice cover is getting younger and thinner on average.

The annual ice duration is getting shorter.

As a consequence of such development, the realization of an “ice-free Arctic Ocean” has become more plausible than ever in the history of man.

Other major implications of the Arctic climate change for the Arctic shipping comprise of alterations in weather and marine conditions as well as different behavior of glaciers and hummocks. In general, there are a few central meteorological phenomena affecting the Arctic shipping: cold temperatures (icing and freezing), low visibility (summer fogs and blowing snow), and rapidly developing unpredictable storms (polar lows). The occurrence and magnitude of these phenomena will alter due to the Arctic climate change.

In conclusion, despite the maritime conditions in the Arctic are undeniably changing, certain characteristic features of the Arctic waters will remain unaltered. Hence the sailing conditions of the Arctic region will not be comparable to those of blue waters at least in the near future, and open-water vessels are very likely to encounter serious hindrances when operating in the Arctic.

3. The presumed alterations in Arctic shipping conditions are manifold in their nature, giving rise to both benefits and hindrances to marine activities.

The total ice extent of Arctic sea ice is diminishing, and the losses of sea ice cover centre on late summer (practically September). The current minimum of sea ice extent is from the year 2012 (see Fig. C), and the previous record was set only in 2007. If the development of Arctic sea ice cover remains unaltered, the Arctic Ocean is likely to reach a momentary ice-free state during the 21st century.

The maritime conditions even in the ice-free state of the Arctic Ocean pose remarkable challenges and difficulties to marine transportation activities, as ice-free Arctic refers to the situation in which the Arctic sea ice extent is less than one million square kilometers for at least five consecutive years.

The changes in the Arctic cryosphere involve also alterations in the composition and thus the behavior of sea ice. Older and thicker ice is thawing faster than the relatively thin first-year ice, so that the relative share of first-year ice increases while the average age of the ice decreases (see Table A). Younger ice cover is more fragile and more vulnerable to external impacts, whereas older ice is more hazardous to vessels.

Less sea ice does not automatically mean more favorable marine conditions or even reduced need for icebreaking services. The summertime disappearance of relatively light first year ice may eventually result in increased drifting of thick multi-year ice, posing thus more substantial hazard to vessels with
minor or no ice-strengthening. In places of narrow passage—such as straits and fragmentary archipelago—floating multi-year ice may pack, forming practically impenetrable obstacles for vessels without notable icebreaking capability.

In general, the warming of the Arctic climate will lead to the shattering of the structure of ice; more calving and thus an increased number of smaller icebergs are to be expected. These icebergs, especially in conjunction with the increased fog in summer, constitute a significant threat to safe shipping activities.

In addition, the loss of sea ice is likely to alter regional weather and marine conditions. The following is to be expected:

- Enhanced atmospheric humidity and cloudiness.
- Changes in upper-ocean stratification, ocean temperature and salinity near the surface.
- More frequent and intense summer fogs.
- Harsher wind conditions and higher waves.
- More sea spray and consequent icing of vessels.
- Increased count and intensity of low-pressure systems (polar lows).

All in all, the decrease of sea ice cover makes the weather and maritime conditions more unforeseeable, and forecasting becomes more difficult.

### 4. The decline in the Arctic sea ice and the related opening of Arctic waters leads to increased level of human activities in the region.

Despite the apparent hindrances to Arctic shipping due to Arctic climate change, the retreat of Arctic sea ice cover will give rise to increased marine access and thus very likely lead to an increased amount of different marine activities in the Arctic region (see Fig. D). The increased access improves the overall conditions of both trans- and intra-Arctic maritime transportation.

<table>
<thead>
<tr>
<th>Ice type</th>
<th>Relative decrease</th>
<th>Absolute decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total ice</td>
<td>3.8 ± 0.3 %</td>
<td>0.48 ± 0.03 × 10^6 km²</td>
</tr>
<tr>
<td>Perennial ice</td>
<td>11.5 ± 2.1 %</td>
<td>0.90 ± 0.17 × 10^6 km²</td>
</tr>
<tr>
<td>Multi-year ice</td>
<td>13.5 ± 2.5 %</td>
<td>0.82 ± 0.16 × 10^6 km²</td>
</tr>
</tbody>
</table>

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**Ice extent and ice area**

*Sea ice extent* and *sea ice area* both relate to the amount of ice on the surface of ocean—that is, the relative shares of frozen and unfrozen surface—but they are usually treated separately.

*Ice extent* refers to the sum of ice covered areas with concentrations of at least 15 %, whereas *ice area* is the product of the ice concentration and the area for which the concentration in question has been measured. In other words, *ice extent* stands for the total area with significant presence of ice, while *ice area* means the share of the surface which is actually covered with ice.

Defined this way, *ice extent* might have more relevance concerning the possibility of maritime activities, whereas *ice area* determines mostly the climatological significance of the ice—such as its influence on the total albedo of certain region.
The most significant trans-Arctic possibilities concern the short cut passages between the Atlantic and the Pacific Oceans, either along the northern coast of North America (the Northwest Passage, NWP) or along the northern coast of Russia (the Northeastern Passage, NEP; sometimes the Northern Sea Route, NSR) (see Fig. E). Also more straightforward options right through the Arctic Ocean, up close or across the North Pole, have been attended, but their relevance at present—and presumably in the near future—is fairly minor.

Distance savings, when comparing trans-Arctic and traditional routes, can be up to 50%. As the distance traveled becomes shorter, fuel consumption and thus emissions decrease, giving rise to significant potential for cost savings. However, savings in distance do not necessarily entail corresponding savings in time or in fuel consumption, since the short cut option may involve notable challenges and obstacles that hinder the journey. The occurrence of sea ice, for example, is likely cause decrease in travel speed and lead to a need of higher output power.

All in all, the usage of trans-Arctic passages must be both technically and economically justifiable, and this sets the definite framework for all future development. Thus, when assessing the feasibility of trans-Arctic passages, a great number of different factors must be taken into account. Such factors include travel distance and time (vessel’s speed), reliability with respect to transit time, the duration and variability of potential ice-free conditions, bunker prices and the overall development of world economy.
possible icebreaker assistance and transit fees, investments in equipment and personnel training, safety in general, as well as risk managing and insurance costs.

The possibility of new intra-Arctic routes relates particularly to an improved access to natural resources, especially oil and natural gas. The improving access to remote reserves of oil and natural gas in the Arctic may lead to notable revisions of strategies concerning petroleum activities, since the Arctic is estimated to contain as much one-fifth of world’s undiscovered oil and natural gas.

However, the estimates of forthcoming intra-Arctic oil and gas production rates vary considerably, as the Arctic conditions pose notable challenges to the efficient and safe utilization of the assumed reserves. Financial aspects hinder the petroleum-related activities as well, since the utilization of Arctic resources has thus far remained fairly expensive compared to the level of costs in more favorable environments.

In addition to the shipping related to the utilization Arctic oil and gas resources, there are other intra-Arctic marine activities whose operating conditions will be altered. For example, fishing and passenger vessels may increase the extent and annual duration of their operations, giving rise to increased amount of journeys and related hazards.

5. The preparedness of potential Arctic marine operators varies, which in conjunction with insufficient shoreside infrastructure gives rise to certain safety concerns.

In general, the regulation of operation in the Arctic is yet rather low and insufficient, and inappropriate equipment and preparations may comprise a serious issue in the Arctic region. There are several factors contributing:

− First, there is no guarantee that the vessels operating in the Arctic are properly equipped and sufficiently ice-strengthened to manage in the Arctic conditions. Apart from the apparent risks due to ice encounters, also icing and freezing may cause ships to lose their operability.

− Second, sailing in the Arctic waters demand very much from the crew. Arctic waters offer significant navigational challenges, and the professional skills of the mariners are tested in everyday situations. Thus far the training of the skillful officers has mostly been on-the-job, with relatively little formal education.

− Third, the lack of proper Arctic shoreside infrastructure hinders determined and rapid response to different incidents, restraining notably the appropriate utilization of Arctic waters. For example, Arctic waters are not in general very well charted, they comprise an area which is not served by any single broadcasting system, and the current search and rescue infrastructure is very limited and regionally varying.

As a result, the consequences of ever larger fleet with varying standards of equipment being exposed to the harsh conditions of the Arctic may be at worst disastrous from the perspective of both human health and environmental welfare.

6. The projected increase of marine activities in the Arctic leads to a considerable statistical risk of humanitarian and environmental disasters.

As well as other marine activities, Arctic tourism is predicted to grow along the disappearance of major barriers. However, many of the cruise vessels traveling to Arctic destinations may not be appropriately ice-strengthened, as the growing demand exceeds the capacity of vessels constructed or designed to operate in Arctic conditions, which in conjunction with the undersized emergency response capabilities of local communities pose a remarkable risk of humanitarian disaster.

Apart from this, spills of oil and other hazardous materials comprise a question of additional concern in the Arctic. The risks related to such spills are particularly notable due to several reasons:

− First, long distances and the presence of sea ice significantly hinder executing appropriate measures.
Second, the cold temperatures of the Arctic region slow down the rate of biological degradation of oil, leading to increased durations and more extensive areas of exposure.

Third, due to its inherent features as a system of natural extremities, the Arctic environment is exceptionally vulnerable to sudden changes. Consequently, even a spill incident of rather moderate degree may in the Arctic conditions result easily in a vast ecological disaster.

7. The emissions from the increased Arctic shipping may have considerable and unpredictable influences to the sensitive Arctic environment.

In addition to the soaring risk of different incidents, the increased marine activities will generate a significant amount of emissions (see Fig. F). Shipping produces a wide spectrum of emission species, including a set of air pollutants—such as sulfate, nitrogen oxides and black carbon—that have considerable warming impacts on the climate, as well as other detrimental effects on human health and the welfare of environment. Emitted in relatively distant locations in the High Arctic, the emissions from Arctic shipping will eventually distribute in a new and thus unforeseen way.

Due to the remoteness and poor accessibility, the Arctic region has remained rather pristine. As a consequence, the current emission levels in the Arctic are relatively low compared to the global averages. In such an environment, even fairly small absolute increases are likely to lead to significant relative increases. Hence the predicted development of the Arctic marine activities potentially causes remarkable alterations in local concentrations in the Arctic.

The uniqueness of the Arctic environment notably complicates managing and controlling the development in the Arctic. As there is no extensive observational history of the behavior of the Arctic environment, the exact influences of the increased emissions in the Arctic region are difficult or nearly impossible to predict. Especially the large-scale interactions between the cryosphere and the climate as well as the presence of multiple feedback mechanisms pose additional challenges to predicting the future of Arctic.

Fig. F. An overview of estimated current and projected future amounts of certain air pollutant emissions from shipping in the Arctic area according to different studies. With regard to the present day estimates, the inventory year is different in the Winther et al. 2014 study. These numbers include possible diversion traffic, whereas fishing vessels are excluded systematically. In addition to this, the numbers of the Peters et al. 2011 study exclude marine activities related to tourism and local re-supply. Data sources: Corbett et al. 2010, Peters et al. 2011 and Winther et al. 2014.
8. The local effects of certain air pollutant emissions—such as black carbon—have special climatical relevance in the snow- and ice-covered areas in the North.

Certain air pollutant emission subspecies are relatively short-lived, so that their full interhemispheric mixing is not possible and thus the related climatical influences are mostly local in nature. Hence, with regard to short-lived air pollutant emissions, the geographical location of the emission sources is of notable significance.

Especially black carbon (BC) emissions are likely to have notable local climatical effects in the Arctic, as the black carbon particles absorb solar heat very effectively. When highly absorbent black carbon particles are deposited to a reflective surface—such as snow or sea ice—they may significantly alter the albedo of the surface and thus notably increase the amount of absorbed solar heat. The increased amount of solar heat in turn leads to warming of the surface and contributes directly to the climate change.

Furthermore, in an environment whose inherent reflectance is particularly high, even fairly low concentrations of black carbon may have considerable regional effects on the albedo. In other words, even rather small absolute amounts of black carbon emissions are capable of substantially increasing the absorbency of relatively large geographical areas, when distributed evenly (see Fig. G). This is why the total magnitude of warming impact from black carbon emissions is potentially more substantial in the Arctic when compared to lower latitudes.

9. The increased black carbon emissions originating in the Arctic region may contribute significantly to the Arctic climate change.

Presumably the most significant positive feedback mechanism in the Arctic is related to the process that involves the increases in temperature and the disappearance of snow and sea ice cover. As the proportion of the highly reflective surfaces—such as snow and sea ice cover—decreases, significantly less reflective surfaces—such as the soil and the ocean—are revealed. As a consequence, more heat from solar radiation is absorbed. (See Fig. H.)

The absorbed heat increases the surface air temperature and causes overall warming of the atmosphere, which in turn contribute to the melting of snow and sea ice. Once again, as the snow and sea ice cover thaw, even more surface that absorbs heat effectively will be revealed to solar radiation.
With regard to the Arctic climate change, such positive feedback mechanisms are of crucial significance. Far enough developed positive feedbacks may be very difficult to halt or even to hinder since they constantly reinforce themselves. In conclusion, it is the feedback mechanisms that are likely to determine the general course of development in the Arctic.

The significance of such positive feedback mechanism also highlights the role of agents that absorb or scatter radiation, both in the atmosphere and on the surface. Among the most essential air pollutants, black carbon absorbs solar heat particularly effectively. Hence black carbon emissions are likely to have specific importance to the positive feedback currently affecting in the Arctic region.

This is the reason why the forthcoming changes in black carbon emission levels in the Arctic are of considerable significance from the climate perspective. Due to the remoteness of the Arctic region, also the increasing Arctic marine activities may have remarkable role with regard to black carbon emission levels in the Arctic—that is, even though the absolute volume of the Arctic shipping might remain relatively low on the global scale.

10. The amount and significance of black carbon emissions from both current and future Arctic shipping have been evaluated.

In order to assess the potential impact of black carbon emissions from the increased Arctic shipping, it has been necessary to estimate the effects of present-day Arctic shipping to the current levels of black carbon concentrations and depositions in the Arctic. Also the related climate impacts of such emissions—expressed as radiative forcing—have been calculated.

The year 2004 marine activities in the Arctic region are estimated to produce about 1.2 thousand tonnes of black carbon emissions annually. The outcomes of two independent studies (Corbett et al. 2010 and Peters et al. 2011) are very similar, implying that at least the magnitude of the estimates is correct. An update to these numbers is produced by Winther et al. (2014); according to their study, the

IV The emission inventories are based on different estimates of Arctic marine activities, which in turn include varying assumptions and definitions, giving rise to certain inconsistencies among the results. For example, there is no established and thus unequivocal geographical definition of Arctic waters, and the coverage of the estimates varies. (Certain vessel types are often excluded from the assessments, mainly due to methodological reasons. For example, the share of fishing vessels may not be included, as the emissions from fishing vessels are based on operating activity instead of the number of trips.)
annual black carbon emissions from Arctic shipping are around 1.6 thousand tonnes in 2012, which is in line with earlier studies.

According to Ødemark et al. (2012), the year 2004 levels of black carbon emissions from Arctic shipping lead to a total radiative forcing of about 1 mW m\(^{-2}\). This can be compared to the radiative forcing of 49 mW m\(^{-2}\) from the carbon dioxide emissions of global shipping (in 2007). It is also noteworthy that the radiative forcing due to black carbon emissions from Arctic petroleum activities is approximately 27 mW m\(^{-2}\) (in 2004).

In general, the black carbon emissions from Arctic shipping are projected to increase substantially. Depending on the underlying assumptions, the emissions are estimated to at least double, but according to certain projections, the emissions may be almost twenty-fold when comparing present-day (2004) levels to the situation in 2050.

The remarkable difference in the magnitude of the projections results above all from the differing presumptions concerning the level of increase in the Arctic marine activities. The more restrained estimates are based on a so-called Business-As-Usual development of the Arctic shipping, whereas the high estimates depend on constant growth of a substantial rate.

The possibility of such a significant growth in Arctic shipping relies on further assumptions with regard to the feasibility of marine activities in the Arctic waters. Thus the implicit suppositions related to the forthcoming development of Arctic sea ice cover and general marine conditions in the Arctic are essential when assessing the reasonability and plausibility of the emission projections.

The increased emissions have impacts on the concentration and deposition of black carbon (see Fig. I). However, the results of Winther et al. (2014) show that the contribution of increased\(^{\text{v}}\) black carbon

\(^{\text{v}}\) An increase of 118 % from 2012 level (from 1.58 to 3.45 thousand tonnes).
emissions from Arctic shipping to Arctic-wide average concentration is yet moderate, merely 3.6% in summertime 2050. Nevertheless, along the diversion routes, local black carbon concentrations are projected to rise over 80% due to increased Arctic shipping.

With regard to the black carbon deposited to snow, the outcomes of studies are twofold. Though the influences to the Arctic-wide or global average rates may be small or even negligible, local-scale effects are undisputable.

According to Browse et al. (2013), the proportion of Arctic shipping to Arctic-wide average is rather small: when assuming high growth in the level of Arctic marine activities, the increased black carbon emissions from Arctic shipping lead to a contribution of merely 0.7% to the total black carbon deposition north of 60°N in 2050. Despite this, regional impacts are projected to be much more considerable, reaching up to 15% over the west coast of Greenland and the Bering Sea.

Winther et al. (2014) indicate a contribution of 1.0% in black carbon deposition in summertime 2050. Local rates may yet be more substantial: over the ocean east of Greenland and in the High Arctic, the levels of black carbon deposition are estimated to be 5% higher as a result of black carbon emissions from increased Arctic shipping.

11. The possibilities of abating emissions from both global and Arctic marine activities are worked out by the International Maritime Organization.

The International Maritime Organization (IMO) has been actively searching ways to cut down emissions from marine activities. Measures affecting both globally and locally have been considered and implemented. Directing the measures to only certain areas and vessel classes is meant to produce substantial results with moderate expenses and hindrances.

For example, the MARPOL Annex VI regulations have been constraining the nitrogen oxide (NOx) and sulfur oxide (SOx) emissions from shipping since 2000 and 1997, respectively. The implementation of such regulations is however partially confined to the certain emission control area (ECAs, see Fig. J), which limits the overall effectiveness of such measures.

VI A remarkable increase from 0.88 (in 2004) to 16.7 thousand tonnes (in 2050).
VII Assuming an increase of 118% from 2012 level (from 1.58 to 3.45 thousand tonnes).

Fig. J. Current and possible future emission control areas (ECAs) by IMO. Source: DNV-GL 2011.
With regard to black carbon, there are certain fundamental issues that hinder implementing regulations and thus gaining abatements. Above all, defining black carbon unequivocally has proven to be a rather difficult task, as it is not comprised of any single combination of elements or compounds. The possibility of performing black carbon emission measurements both accurately and cost-effectively has been central issue concerning the development of the appropriate definition.

Despite the consensus on the pragmatic nature of the definition, some disagreements among IMO member states over possible measurement technologies have hidered the overall process. IMO member states generally agree that at least the preliminary definition may be purely technical and thus not strictly scientific, but the eventual selection of approved measurement technologies has posed difficulties and retardments.

IMO has also provided studies focusing on black carbon emission abatement technologies. When assessing such technologies, various factors have to be taken into consideration. For example, the possible consequences to other species of emissions as well as the commercial availability and the implementation time of the technologies are of crucial importance. In general, the most efficient alternative is likely to be a combination of different single solutions. (See Table B.)

Table B. The most promising black carbon abatement measures according to an IMO-related study. Data source: Lack et al. 2012.

<table>
<thead>
<tr>
<th>Abatement measure</th>
<th>BC reductions (%)</th>
<th>CO₂ reductions (%)</th>
<th>Technology maturity</th>
<th>Implementation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEDI (Energy Efficiency Design Index)</td>
<td>30.0</td>
<td>30.0</td>
<td>Commercially available</td>
<td>Over 10 years</td>
</tr>
<tr>
<td>Slow steaming (with de-rating of the engines)</td>
<td>15.0</td>
<td>18.5</td>
<td>Commercially available</td>
<td>1-5 years</td>
</tr>
<tr>
<td>Water in Fuel Emulsion (WIFE)</td>
<td>70.0</td>
<td>0.0</td>
<td>Commercially available</td>
<td>Less than a year</td>
</tr>
<tr>
<td>Heavy Fuel Oil (HFO) distillate</td>
<td>52.0</td>
<td>7.0</td>
<td>Commercially available</td>
<td>Less than a year</td>
</tr>
<tr>
<td>Liquified Natural Gas (LNG)</td>
<td>93.5</td>
<td>22.5</td>
<td>Demonstrations performed</td>
<td>1-6 years</td>
</tr>
<tr>
<td>Diesel Particulate Filters (DPF)</td>
<td>85.0</td>
<td>-3.5</td>
<td>Commercially available</td>
<td>Less than a year</td>
</tr>
<tr>
<td>Exhaust Gas Scrubbers (EGS)</td>
<td>60.0</td>
<td>-3.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

12. The health and environmental issues related to air pollutant emissions are relatively independent of climatical mechanisms.

Although many air pollutant emission species have effects on both climate and the welfare of humans and natural environment, the underlying mechanisms are separate, and thus the related effects should be assessed separately.

It is important to notice that the same amount of air pollutant emissions may have moderate or even negligible effects on climate change but yet have significant detrimental effects on human health and environmental welfare. In other words, though the impact of certain air pollutant emission abatement on the climate would be debatable, the gained abatement may yet lead to other benefits of remarkable scale.

With regard to black carbon emissions, the overall message is rather clear: despite several studies indicate that the total amount of black carbon emissions from future Arctic shipping will remain on a moderate level, cutting the emissions may still have notable beneficial effects.

The global or even Arctic-wide climate impacts of black carbon emissions from future Arctic shipping may be reasonably challenged, but the effects of increased Arctic marine activities on both local black carbon concentrations and the amount of black carbon deposited to snow and ice cover are nevertheless indisputable. The projected changes have local influences: local warming as well as local health and environmental detriments are to be expected.
13. In order to achieve long-term climate change mitigation goals, the focus must remain on carbon dioxide emissions, though the black carbon emissions and emission abatements may have notable role with regard to the climatical development in the most vulnerable areas.

Though the climate impact from black carbon emissions is undeniably significant in the global scale, the essential role of carbon dioxide emissions must not be understated. After all, carbon dioxide is the single most significant greenhouse gas, and carbon dioxide emissions are responsible for 55-60 % of anthropogenic radiative forcing.

Moreover, there is a significant difference in the lifetime of black carbon and carbon dioxide. Black carbon is considered a short-lived climate forcer (short-lived climate pollutant in some occasions), since it has a relatively short lifetime compared to carbon dioxide. The lifetime of black carbon is from days to weeks, whereas carbon dioxide has effects on the atmosphere for hundreds or thousands of years.

Thus the only way to gain long-term climate change mitigation goals is to continue pursuing abatements of carbon dioxide emissions. Despite this, as reducing emissions of long-lived greenhouse gases will have an effect only on longer time scales, cutting down short-lived emissions—such as black carbon—can help to reduce near-term global warming and its impacts, particularly in regions most vulnerable to climate change—such as in the Arctic.
Introduction

Despite the long-lasting and persistent human endeavors, Arctic waters have thus far remained fairly pristine, as the particularly harsh conditions have posed remarkable and often overwhelming challenges to Arctic mariners (AMSA 2009, Østreng et al. 2013). In fact, most of the Arctic region has been practically inaccessible even to ice-strengthened vessels, especially in wintertime (AMSA 2009, Østreng et al. 2013). Hence, the extremely sensitive Arctic environment has had special intrinsic value as a reminder of natural-state planet Earth.

The situation may however alter significantly in the near future, as the Arctic sea ice is currently diminishing at an unforeseen rate (ACIA 2005, AMAP 2011b, IPCC 2013). Such a development results from the warming of the Arctic climate, which is a drastic manifestation of the global climate change (IPCC 2013). For example, since 1980 the increase in average temperature in the Arctic has been twice the global rate, and the surface air temperatures measured in the Arctic since 2005 have been higher than for any five-year period ever recorded (AMAP 2011b).

Both the extent and volume of the Arctic sea ice are decreasing, and the ice is getting both thinner and younger on average, as the share of thick multi-year ice is reducing (IPCC 2013). The current minimum of total Arctic sea ice extent is 3.44 million km² from the year 2012, while the previous record was set only in 2007 (IPCC 2013). In general, there is least ice in the Arctic region during the late summer months (from August to September), when the melting has stopped but the freezing has not yet begun. In addition to the loss of summertime ice cover, also the ice duration has shortened, as ice both retreats earlier in spring and advances later in autumn; the annual sea ice duration has regionally shortened up to several months between 1979—2011 (IPCC 2013).

Comprehending the manifold mechanisms underlying the Arctic climate change has proven to be a particularly demanding task, as there are several complex issues related to the large-scale interaction between the cryosphere and the climate (AMAP 2011b). Measuring and predicting such interactions is difficult, posing thus additional challenges to projecting the future of Arctic climate and cryosphere.

The particularly high rate of warming in the Arctic compared to global average is however predicted to remain unaltered (IPCC 2013), and an Arctic-wide increase of even 13 °C in late fall at the end of the 21st century seems possible (Overland et al. 2013). The potential effects of implementing emission mitigation policies and technologies are of remarkable significance, but the overall trend of warming is yet inevitable (Overland et al. 2013).

Also, the diminishing of the Arctic sea ice is projected to continue; the disappearance of summertime Arctic sea ice and thus an ice-free Arctic seems rather likely by the end of 21st century (IPCC 2013). Additionally, the models used in projecting the development of sea ice extent have proven to somewhat underestimate the occurring change on average (Wang & Overland 2012). Thus the rates of decrease in the Arctic sea ice cover might eventually be even more drastic than the models indicate.

In general, the concept of “ice-free Arctic Ocean” is essential in assessing the future of Arctic shipping. The ice-free Arctic Ocean means that the Arctic sea ice extent is less than one million km² (IPCC 2013). Hence, there will nevertheless be sea ice in the Arctic in the future even in such “ice-free” summertime situation, implying that the marine conditions will remain challenging (AMSA 2009, Østreng et al. 2013).

The overall decrease of ice cover and the shortening of ice duration are yet likely to open up new routes for maritime transportation, both trans-Arctic passages and new alternatives within the Arctic region. The most significant transit possibilities via Arctic waters concern the short cut passages between the Atlantic and the Pacific Oceans, either along the northern coast of North America—the Northwestern Passage—or along the northern coast of Russia—the Northeastern Passage (AMSA 2009, Østreng et al. 2013).

Though the changes in sea ice cover may undoubtedly result in an increased access to certain areas in the Arctic region, the occurring changes will be manifold and involve more dimensions than mere benefits to maritime transportation. The major implications comprise at least of alterations in weather and marine conditions, different behavior of glaciers and hummocks, and the consequences of ever larg-
er fleet with varying standards of equipment being exposed to the harsh conditions of the Arctic (ACIA 2005, AMSA 2009, Østreng et al. 2013). In addition, there are the increased emissions, which will distribute geographically in a new and thus unforeseen way (Corbett et al. 2010, Peters et al. 2011).

The vulnerability of the Arctic region results in part from its remoteness and the fact that the regional overall emission levels have remained rather low as the most remarkable sources of emissions have thus far located at lower latitudes and thus outside the Arctic region (Dalsøren et al. 2013, IPCC 2013); hence even fairly small absolute increases in Arctic emissions may eventually lead to significant relative increases (Corbett et al. 2010, Peters et al. 2011). To be sure, notable transportation of the emissions has occurred before and will occur in the future, but the geographical location of the emission sources still matters—especially with regard to certain relatively short-lived emissions (AMAP 2011b, Browse et al. 2013, Shindell & Faluvegi 2009, UNEP 2012).

The role of global shipping with regard to greenhouse gas and certain air pollutant emissions is of significant magnitude (Buhaug 2009, UNEP 2012). Such emissions have both long and short-term warming impacts on the climate, as well as other detrimental effects on human health and the welfare of environment (UNEP 2012). The observed boom in global shipping activities in recent decades is projected to continue, leading presumably to increased emission levels and thus to a considerable climatical and environmental burden (Buhaug 2009).

Also the amount of Arctic shipping is projected to increase notably, even more than the global average (Corbett et al. 2010). This is first and foremost due to the improved maritime access in the Arctic region—especially during the summertime—which is likely to give rise to certain commercial potential (AMSA 2009, DNV 2010, Khon et al. 2010, Liu & Kronbak 2010). Though the eventual feasibility of the Arctic marine passages and thus the exact Arctic-specific rates of growth remain open, the presumed increase in Arctic shipping probably leads to considerable increases in emission levels within the currently rather remote Arctic region (Corbett et al. 2010, Peters et al. 2011).

The significance of emissions from Arctic shipping is above all based on their bearing to the spatial distribution of certain air pollutant emission species with relatively short lifetime—of which black carbon is a noteworthy example (Dalsøren et al. 2013, Winther et al. 2014, Ødemark et al. 2012). Black carbon emissions are of particular interest in the Arctic region, as black carbon may deposit to surfaces with high reflectivity—such as snow and sea ice—causing a remarkable increase in the amount of solar heat absorbed, which in turn leads to the melting of sea ice and to the decrease of sea ice extent (AMAP 2011a). Furthermore, there is evidence that in the case of very reflective surface, even relatively low concentrations of deposited black carbon may be of great significance (Flanner 2013).

The specific role of the Arctic marine activities with regard to Arctic black carbon concentration levels is however open to dispute, and the projected increases in black carbon emissions from Arctic shipping may be relatively so small that their influences to the Arctic-wide average remain unmeasurable due to the enormous scale of natural emission variability (Browse et al. 2013). Despite such possibility, certain health and environmental advantages related to potential black carbon emission reductions are indubitable (UNEP 2012).

To be sure, there are many other species of emissions that contribute to the warming of Arctic climate remarkably. In addition, the essential connection between Arctic and global climate change must be borne in mind. Hence, the significance of carbon dioxide—the most important single anthropogenic greenhouse gas—must be emphasized, as the only way to mitigate global climate change in the long term is to reduce the levels of carbon dioxide emissions (IPCC 2013, UNEP 2012). Nevertheless, reductions in, for example, levels of black carbon emissions are yet relevant, as they may comprise an effective measure to gain relatively fast response (UNEP 2012).

The International Maritime Organization (IMO) has been working on policies aiming at efficient reductions in certain species of emissions (Buhaug 2009), and the global marine industry has been forced to develop solutions in order to fulfil the requirements set by the international authorities. The focus has been on nitrogen and sulfate oxides, but IMO has more recently acknowledged the potential significance of black carbon from shipping. For example, the exact definition of black carbon as well as the most suitable measurement and abatement technologies are currently under debate (IMO 2011b, IMO 2014, Lack et al. 2012). All in all, there is a wide range of methods and technologies for gaining emission abatements, and the most efficient alternative is likely to be a combination of different single solutions (Lack et al. 2012).
Besides the work in the field of emission regulations, IMO has taken action in order to define the standard of equipment with regard to vessels operating in polar waters (IMO 2010). The prime aim of IMO’s polar work is to ensure the same level of safety for persons, the environment and the ships in Polar waters as in other waters. Thus far IMO has published unbinding guidelines and developed a system of Polar Classes, but no conclusive agreement on implementing mandatory IMO Polar Code has yet been achieved (Østreng et al. 2013).

The overall objective of this review report is to introduce the field of Arctic shipping and the framework in which the Arctic marine activities take place. The report comprises of assessments of natural, social, administrative, technological and regulatory dimensions that define the conditions for Arctic shipping, while the focus of the report is on shipping-based emissions and related issues.

It is clear that the framework for Arctic shipping in its entirety is a very complex subject consisting of a vast amount of factors, so that a thorough analysis is well beyond the scope of the report. Instead, the report aims to provide such elementary background information that is essential for comprehending the current and forthcoming development in the Arctic region.

In order to fulfil its aim, the report makes use of the most important publications of the established international organizations—such as the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC 2013), the Second IMO Greenhouse Gas Study by the International Maritime Organization (Buhaug 2009), and the Fifth Global Environment Outlook by the United Nations Environment Programme (UNEP 2012).

As the report discusses above all Arctic issues, the research related to Arctic Council and its working groups forms a database of remarkable importance. Among the major Arctic Council—related sources are the Arctic Climate Impact Assessment (ACIA 2005), the Arctic Marine Shipping Assessment report (AMSA 2009), and the Snow, Water, Ice and Permafrost in the Arctic (SWIPA) report (AMAP 2011b).

In addition to these rather comprehensive studies, a considerable amount of relevant, more narrow-scoped scientific articles and reports as well as statistical and other factsheets by different authorities are cited. With regard to the most recent events and turns, also a selection of online news sites is referred to.

The report is divided into four sections; the sections discuss the history of Arctic shipping, Arctic climate change, shipping conditions in the changing Arctic, and the emissions from shipping in the Arctic, respectively. Each section includes several subsections and a short introduction to the subject matter, helping the reader find the relevant information effectively.
2. A brief history of shipping in the Arctic

In this section, the history of Arctic shipping is studied from a few different perspectives. First, the era of exploratory expeditions—reaching to the beginning of 20th century—and the most significant relevant events are discussed. The second subsection covers the geographical and geopolitical issues related to the Arctic region, including certain questions of defining the marine routes as well as the development and the promotion of the routes during the cold war period. The last subsection focuses on more recent turns in the Arctic shipping, assessing above all the utilization rate of the commercial potential of the trans-Arctic passages.

2.1. Conquerors and endeavors

Arctic waters have been subject to human interest and endeavor for thousands of years. The history of shipping in the Arctic waters reaches approximately to 325 B.C., as the Greek navigator Pytheas sailed northward, reaching the vicinity of Iceland and perhaps even Greenland. About one thousand years later, in the 9th century, the Scandinavian Vikings performed significant expeditions in the Arctic area, colonizing Iceland and Greenland. Their journeys extended eventually to the northeast coast of North America. (AMSA 2009.)

The possibility of a short cut marine passage from Europe to Asia drove European navigators to survey both the complex network of Canadian Arctic Archipelago and the northern coastline of Russia in the 15th century. Neither of the alternative routes proved to be of easy access, and the explorers continuously risked their health and lives in the harsh conditions during the courageous journeys. (AMSA 2009.)

The eventual motives for seeking and upholding Arctic shipping routes have varied according to historical era and the related ideals. Even though the main emphasis may at times have been on discovering new, issues related to financial and/or national security always have bearing to enterprises of such remarkable scale (Østreng et al. 2013).

The expeditions caused indeed notable expenses, comprising significant portions of national budgets. For example, the Second Kamchatka expedition—one of the largest expedition projects in history and completely financed by the Russian state—reached the estimated sum of 1.5 million rubles, corresponding to one-sixth of the total income of the Russian state for the year 1724 (AMSA 2009).

Though the conquerors from Great Britain, the Netherlands and Russia paid high price for their endeavors during the centuries, it was not until 1879 that the complete transit through the short cut route along the northern coastline of Russia—the Northeastern Passage (NEP)—was accomplished. The Finnish-Swedish explorer Adolf Erik Nordenskjöld reached the Bering Strait after having carried out a full passage from Europe, spending one winter along the way. (AMSA 2009.)

The route through the Canadian archipelago—the Northwestern Passage (NWP)—was conquered even later, as the task was first completed by Norwegian explorer Roald Amundsen only in 1906. It took altogether three winters to complete the voyage, and the significance of help from the Inuit was enormous, as they practically enabled his survival through the harsh Canadian winters. (AMSA 2009.)

2.2. Geographical and geopolitical issues

The charting of the Arctic region has a colorful history of its own, and it represents for its part the historical situation concerning scientific progress as well as the global political matters. Despite this, the focus of this subsection is on the geographical nature of the most central areas and on the geopolitical questions of 20th century. Also certain obscurities among the naming of shipping routes are discussed.

Although both Northeastern and Northwestern passages are often referred as clearly defined short cut routes between the Atlantic and the Pacific Oceans, they both comprise of a multitude of alternative routes or entire sea areas to be exact. The NWP eventually consists of seven different routes, of which six run through the southern part of the archipelago (Østreng 2013). Similarly, the easternmost part of
the NEP—the share of the NEP that is often referred to as the Northern Sea Route (NSR)—practically covers the whole sea area between Novaya Zemlya and the Bering Strait (Ragner 2000).

Furthermore, the terms “Northeastern Passage” and “Northern Sea Route” are often used as synonyms in a rather equivocal way. However, a clear distinction can be made, as the Northeast Passage is a historic term for the transit route north of Russia linking together the Northern Atlantic and Northern Pacific Oceans—being thus a somewhat abstract term without strictly defined borders or end-points—whereas the Northern Sea Route stretches according to the official definition (by Russians) from the Novaya Zemlya islands in the west to the Bering Strait in the east (see Fig. 1). (Ragner 2000.)

The history of the term “Northern Sea Route” reaches back to year 1932, when the Council of People’s Commissars of the USSR established the NSR as a separate part of the NEP. In this connection the exact endpoints of NSR were also defined: from Novaya Zemija in the west (meridian 168 degrees 58 minutes and 37 seconds west) to the Bering Strait in the east (parallel 66 degrees north). Since then, the NSR was an administered, legal entity under full Soviet jurisdiction and control. (Østreng et al. 2013.)

However, the relevance of the NEP as an international waterway had already diminished after the Russian Revolution in 1917, after which the route became practically inaccessible to non-Soviet vessels (Ragner 2000). In the Soviet era—ending in the formal opening of the NSR to foreign vessels on 1st July 1991—the enclosed NSR was gradually developed as an internal waterway, supporting various purposes such as industrial, military and scientific endeavors (Østreng et al. 2013). Most remarkable landmark

Fig. 1. The Arctic marine area. Source: AMSA 2009.
voyages during this era include the 1977 voyage of the Arktika to the geographic North Pole, and the first complete high latitude passage by the surface vessel Sibir in 1978 (AMSA 2009).

In the meanwhile, the utilization of the Northwestern Passage was topical issue among western countries. The possibilities of the NWP were assessed from both economic and national security-related perspectives. For example, the Distant Early Warning (DEW) line—comprising of a linked chain of 63 communication and radar systems, spanning approximately 5,000 km—was set up to detect incoming Soviet bombers during the Cold War. The enormous building project was carried out between 1954 and 1957, involving more than 300 ships carrying more than 300,000 tonnes of cargo during the two summer navigation seasons of the North American Arctic. (AMSA 2009.)

The commercial potential of the NWP was tested and promoted in 1969, as the ice-strengthened American supertanker Manhattan transited the Canadian Archipelago from the east coast of the USA to Prudhoe Bay in Alaska, returning the same way in the following year. Such demonstrations of the capabilities of modern vessels undoubtedly increased public and governmental interest in Arctic shipping, but raised questions about the environmental risks due to the harsh conditions, too. To be sure, Manhattan encountered serious challenges, as it got stuck in the ice no less than 25 times during the outward trip, and the sea ice knocked out a huge panel from Manhattan’s hull on the return journey—resulting in a spill of 15,000 barrels of ballast water. (Østreng et al. 2013.)

2.3. The recent development of the trans-Arctic marine traffic

Despite the undisputed achievements in the field of Arctic shipping, neither of the transit passages has turned out to be success of grandiose scale. This is mainly due to the challenging Arctic marine conditions, but certain questions concerning the governance of trans-Arctic passages may also have decreased the level of utilization (such issues will be in detail discussed later, in section 4).

During the period between 1903 and 2004—roughly the first century of transit marine activity—there were altogether 181 transits through the Northwestern Passage, implying an average of mere 1.7 transits per year. In this period, 67 separate vessels completed the passage, carrying 15 different flags. However, 63 % of the transits were Canadian flag, mainly Canadian Coast Guard icebreakers. In the same period, 175 partial transits were recorded through the waters of the Canadian Arctic archipelago. (Østreng et al. 2013.)

The activity among the NWP has increased in the recent decades. For example, until the 1970s, only 9 complete passages were made, whereas there were 26 transits in merely 2010 (Østreng et al. 2013). A landmark in the commercial use of the NWP was set in 2013, as an ice-strengthened sea freighter became the first bulk carrier to transit through the passage; the Danish-owned 75,000 DWT Nordic Orion left Vancouver on 17th September, heading for the Finnish port of Pori (National Post 2013).

The situation with regard to the Northeastern Passage and the Northern Sea Route is similar, though the relevant numbers are somewhat higher. While the internal usage of NSR reached a notable level already in the Soviet era, the number of transit voyages has remained rather low. The NSR has thus mostly served regional developmental purposes, and the level of activity was considerable. For example, more than 400 Soviet ships were active in cargo shipments in the 1980s, and the cargo shipping peaked at 6.58 million tons in 1987. Since then, the volume of cargo shipments decreased rather steeply, and an all-time minimum of 1.5 million tons was reached in 1998. (Østreng et al. 2013.)

More recently—in the 2010s—the commercial transit use of NSR has been increasing. The total number of vessels transiting through the NSR was 71 in 2013 (with 25 vessels under foreign (non-Russian) flags from altogether different 11 states), implying an increase of 54 % from 2012 (NSR Information Office 2014). The increase in cargo volume from 2011 to 2012 was as much as 53 % (Barents Observer 2013d), and the total volume of cargo was approximately 1.4 million tonnes in 2013, resulting thus in an increase of merely 7.5 % from the 2012 level (NSR Information Office 2014). In addition, the first ever container-transporting vessel transited along NSR in 2013; the 19,000 DWT “Yong Sheng” operated by China’s state-controlled Cosco Group from China was bound for Amsterdam (Barents Observer 2013b).
3. Climate change in the Arctic

The global climate change has significant effects also in the Arctic. In fact, the Arctic seems to be the region in which the process is most clearly visible, as the Arctic climate is changing notably faster than the global average. The occurring change is usually measured by observing mean temperatures, as the changing temperatures illustrate effectively the overall development. Furthermore, such data are relatively easy to gather and thus fairly extensively available. In short, based on a large observational database, the global warming is undoubtable, and the phenomenon culminates in the Arctic.

In this section, the Arctic climate change is scrutinized from a few different perspectives. The main objective of this section is to provide an extensive overview on the mechanisms affecting in the Arctic region, covering both climate and cryosphere—and their interconnections. However, the focus of the section is on observed and predicted impacts on climate and cryosphere, not on the emissions resulting in such impacts. The role of certain emissions—and the related significance of Arctic shipping—is discussed later on, in the section 5.

First, the historical temperature record of the Arctic is examined. Both short-term and long-term developments—as well as periodical patterns—are taken into account. Second, the peculiarity of Arctic region is explicated, as the concept of Arctic amplification and the related feedback mechanisms are introduced. Third, special attention to the effects of certain air pollutants on the Arctic radiative budget is paid. Fourth, issues related to cryosphere are discussed, the emphasis being on the recent rates of decrease in Arctic sea ice cover. In conclusion, some projections of the future development concerning the Arctic conditions are presented, illustrating the scope of possible directions on one hand, and the difficulty of making appropriate predictions on the other.

3.1. Historical temperature record

The temperature in the Arctic has warmed approximately 0.09 °C per decade over the period from 1900 to 2003, compared to the global average of 0.06 °C per decade (ACIA 2005). Corresponding rates for years from 1964 to 2003 are 0.40 °C per decade and 0.25 °C per decade, respectively, which indicates that the warming has both accelerated and spatially differentiated (ACIA 2005). Moreover, since 1980 the increase in average temperature in the Arctic has been twice the global rate—approximately 0.5 °C per decade (IPCC 2013)—and the surface air temperatures measured in the Arctic since 2005 have been higher than for any five-year period ever recorded (that is, highest in the last 130 years) (AMAP 2011b).
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Fig. 2 visualizes the changes observed at land-based weather stations in the Arctic for over a century of time. Slight oscillation in the observations is perceivable, but the general trend of warming is clear.

Local changes in the average temperature are even more drastic than the Arctic averages: warming rates of approximately 1 to 2 °C per decade in northern Eurasia and north-western North America between 1966 and 2003 have been reported (ACIA 2005).

However, the changes observed do not spread evenly over the year, but they are centered seasonally. Warming is greatest in autumn and early winter and less significant over the rest of the year. Over the Arctic Ocean, temperatures over the past ten years have been over 4 °C warmer in autumn and winter compared to the average for 1951—2000. No greater increase in temperature was observed at any time of year anywhere else on Earth. (AMAP 2011b.)

Periodical climate patterns that for their part affect the Arctic are known to exist, but their general effect is unclear and should not be overstated. The Arctic Oscillation (AO) is such a pattern, and its influence on Arctic weather is widely recognized. The Arctic Oscillation is characterized by difference in air pressure over the High Arctic relative to lower Northern latitudes. The cycle of the oscillation consists of positive and negative phases. In the positive phase, low pressure over the High Arctic pulls warmer and wetter air northwards, which contributes to the rising of observed temperatures. In the negative phase, pressure is high in the far North and the Arctic is cold and dry. (AMAP 2011b.)

Although the negative phase of the Arctic Oscillation has occurred commonly in recent years, overall Arctic temperatures have continued to rise. Also, despite the appropriate consequences of a very negative phase observed elsewhere (e.g. Central Europe has been extremely cold) the High Arctic has stayed relatively warm. These inconsistencies seem to imply that the recent record-high Arctic temperatures cannot be explained by the phases of the Arctic Oscillation, but there must be other mechanisms underlying the changes. (AMAP 2011b.)

Likewise, the existence of possible long-term natural patterns and their manifestation in recent trends has been considered. Earth has undoubtedly come across both cold and warm periods of time, and the changes in mean temperatures between these historical extremes may appear to be of different magnitude compared to the more recent rates of change. For example, change rates of about 10 to 15 °C per decade may have occurred in the history of Earth. (AMAP 2011b.)

However, the more recent rates of warming represent a substantial change in the unusual long-term stability of Arctic temperatures. In the light of the last two thousand years the 20th century constitutes a prominent deviation which seems to exceed the limits of natural variation, as Fig. 3 illustrates. Thus, the
ongoing change should not be neglected solely on the basis of geological history, and its implications deserve serious and exhaustive examination. (AMAP 2011b.)

3.2. Arctic amplification and positive feedback

The exceptionally high rate of warming in the Arctic has been recognized by scientists, and special notice of it has been taken. The phenomenon is generally known as polar amplification or Arctic amplification, of which the latter is more precise expression as there seems to be a lack of equivalent in the polar areas of the Antarctic. Thus, the Intergovernmental Panel on Climate Change (IPCC 2013, 1062) defines the Arctic amplification as “the 67.5 °N to 90 °N warming compared to the global average warming for 2081—2100 versus 1986—2005”.

The positive feedback which the interaction of rising temperature and the melting snow and sea ice constitutes is in the core of Arctic amplification. A positive feedback refers to such development of a system that reinforces an already occurring tendency. In other words, a positive feedback occurs when a change in one part of the system drives a change in another part of the system, accelerating once again the original change. In short, positive feedbacks magnify or amplify change. (AMAP 2011b.)

Presumably the most significant positive feedback in the Arctic is related to the process that involves the increases in temperature and the disappearance of snow and sea ice cover. The feedback in question originates in the reduced regional albedo (reflectivity) that is caused by the melting of snow and sea ice. As the effectively reflective snow and sea ice cover decreases, more heat is absorbed from solar radiation. The heat absorbed to the ground and the ocean does not vanish, but it drifts further causing increases in surface air temperature and overall warming of the atmosphere. Such occurrence leads once again to the melting of snow and sea ice, which in turn means that even more heat absorbing surface will be revealed to solar radiation. Fig. 4 illustrates the essential dynamics. (IPCC 2013.)

The hypothesis of above-mentioned positive feedback is supported by the observation that the greatest increases in temperature have happened particularly in regions where the sea ice has disappeared at the end of the summer. However, the issue is not only about the total extent of sea ice and thus the extent of effectively reflecting surface, but the process affects also the composition and the average age of the Arctic sea ice. These kinds of changes in the ice cover have in turn an influence on the dynamics and the overall behavior of the sea ice, which makes the whole rather complex and difficult to manage. (AMAP 2011b.)

Feedbacks can be very complicated and comprise large totalities with many internal and thus hidden connections. It is generally acknowledged that feedbacks are the least well-understood aspects of the cryosphere system. Nevertheless, their importance is crucial, and managing and mitigating the cli-
Climate change requires better and deeper understanding of feedbacks. For example, there are more than 30 already recognized feedback mechanisms at work in the Arctic, and seven out of eight most prominent are positive (that is, amplifying change) by nature. (AMAP 2011b.)

The significance and seriousness of the supposed positive feedback lies in the fact that far enough developed positive feedback may be very difficult to halt or even to hinder since it constantly reinforces itself. Thus, considering a harmful and undesired tendency, an intervention made as soon as possible will be easiest to carry out and will demand least resources. First and foremost, the key factors contributing to the feedback loop have to be figured out if appropriate measures are to be implemented.

### 3.3. The significance of air pollutant emissions

As to the described positive feedback mechanism that possibly determines the general course of development in the Arctic, the role of agents that absorb or scatter radiation in the atmosphere becomes particularly significant. Human activities—power generation, industry and transport par excellence—also produce such radiation absorbing and scattering agents that have impacts on the radiative budget of climate.

For the purposes of this study, the emissions of these radiative agents from anthropogenic sources are referred as air pollutant emissions. However, it is noteworthy that the air pollutant emissions in question have also other considerable influences on human health and the welfare of natural environments. Furthermore, some subspecies of air pollutant emissions—such as nitrogen oxides—may not affect the radiative budget remarkably in themselves, but act as precursors to more significant radiative forcers.

The emissions of different kinds of particles originating in combustion processes form a notable subcategory of air pollutant emissions. This share of total air pollutant emissions is usually referred as particulate matter (PM). Particulate matter is a manifold mix of chemical compounds, covering for example ash, sulfate, organic carbon-based material as well as non-organic black carbon (see section 5.2 for details).

The different components of PM contribute to the overall radiative budget in various ways. Sulfate and organic carbon (OC) scatter solar radiation as aerosols, whereas black carbon (BC) is a rather efficient absorbent. Also the possible indirect effects related to cloud forming mechanisms have to be taken into account, as emitted particles may act as cloud condensation nuclei. Increased droplet number densities and related changes in the cloud reflectance and lifetimes lead to considerable negative forcing. (IPCC 2013.)

Considering the Arctic, one especially noteworthy subspecies of particulate matter is BC, as it is able to alter the radiative budget in the Arctic particularly effectively. This is due to the fact that BC can absorb and convey heat effectively both as aerosol and when deposited to a surface. In the latter option the total reflectivity of the surface may alter substantially, especially in the case of snow or ice covered surface, whose inherent reflectivity is high. (AMAP 2011a.)

BC has thus a double warming effect in the Arctic: first, BC can effectively absorb heat in itself; second, when deposited to a reflective surface, BC can notably increase the absorbency of large geographical areas. Furthermore, in the case of very reflective surface (such as snow or ice), even relatively low concentrations of deposited BC may be of great significance (Flanner 2013). Hence, BC is likely to have specific importance to the positive feedback currently affecting in the Arctic region.

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1 Radiative budget (sometimes radiative equilibrium) refers to the cumulative overall balance of radiative forcing (RF). Radiative forcing may be positive or negative, according to the presumed effect on surface temperature. IPCC (2013, 13) defines radiative forcing as follows: “Natural and anthropogenic substances and processes that alter the Earth’s energy budget are drivers of climate change. Radiative forcing (RF) quantifies the change in energy fluxes caused by changes in these drivers for 2011 relative to 1750, unless otherwise indicated. Positive RF leads to surface warming, negative RF leads to surface cooling. [...] The strength of drivers is quantified as radiative forcing in units watts per square metre (W m⁻²).”
3.4. Sea ice

As has been acknowledged above, sea ice and its dynamics have great significance regarding the feedback mechanisms that possibly determine the general course of development in the Arctic. Thus, the possible transformations in the Arctic sea ice cover are likely to have remarkable and far-reaching consequences. The Arctic sea ice cover has hitherto experienced major changes. These changes involve not only the total extent of the ice, but also the composition and the average age of the ice.

Prior to examining the past and the ongoing transformation processes in the Arctic sea ice, a few general notes about the Arctic marine cryosphere and its characteristics are appropriate. Arctic sea ice cover varies seasonally, with average ice extent varying between about 6×10^6 km^2 in the summer and about 15×10^6 km^2 in the winter (IPCC 2013). However, the extent and the actual area of sea ice are usually treated separately. Ice extent refers to the sum of ice covered areas with concentrations of at least 15 %, whereas ice area is the product of the ice concentration and the area for which the concentration in question has been measured (IPCC 2013). In other words, ice extent stands for the total area with significant presence of ice, while ice area means the share of the surface which is actually covered with ice.

Defined this way, ice extent might have more relevance concerning the possibility of maritime activities, whereas ice area determines mostly the climatological significance of the ice—such as its influence on the total albedo of certain region. However, the area of ice does not determine the rate of occurring absorption solely, as the albedo of sea ice itself is strongly dependent on the surface state of the ice. In this regard, snow-covered ice differs from bare ice, and melt-pond distribution as well as the proportion of open water are to be noted (see also Fig. 4) (ACIA 2005).

In recent decades, both the extent and the area of Arctic sea ice have drastically decreased. In addition, changes in the thickness and thus in the volume of sea ice also indicate that the total Arctic ice cover is substantially diminishing. The proportions of perennial and multi-year ice^2 have declined as well, which makes the ice cover more fragile and more vulnerable to external impacts (AMAP 2011b).

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^2 Perennial ice is that which survives the summer, whereas multi-year ice is ice that has survived at least two summers (IPCC 2013).
The extent of Arctic sea ice has decreased 3.8 ± 0.3 % (0.48 ± 0.03×10⁶ km²) per decade between 1979—2012. The extent of perennial ice has decreased notably faster, 11.5 ± 2.1 % per decade, and the rate for multi-year ice has been as much as 13.5 ± 2.5 % per decade. The corresponding rates for ice area are 12.5 ± 2.1% and 14.7 ± 3.0% per decade, respectively. Concerning perennial and multi-year ice, the more negative trend in ice area than in ice extent indicates that the average ice concentration has also been declining. (IPCC 2013.)

There is additional evidence indicating that the ice cover is becoming younger. The volume of multi-year ice, for example, decreased 42 % between 2005—2008 (AMAP 2011b). Also, the annual mean ice thickness has declined from a peak of 3.6 m in 1980 to 2.4 m in 2000, which in conjunction with the known relative thickness of older ice implies a decrease in the average age of ice (IPCC 2013). Fig. 5 illustrates the overall development in the age distribution of the Arctic sea ice and the geographical location of the changes occurred.

The decreases in both concentration and thickness weaken sea ice, reducing its resistance to wind forcing. As atmospheric analyses do not show stronger winds but the average drift speed has actually increased, the hypothesis of decreased concentration and thickness seems even more plausible. (IPCC 2013.)

The current minimum of sea ice extent is 3.44×10⁶ km² from the year 2012 (see Fig. 7), the previous record was set in 2007 (4.22×10⁶ km²). The difference of 18.5 % between these minima may seem rather astonishing, but the low in 2012 was probably caused in part by an unusually strong storm
in the Central Arctic Basin. In general, the losses of sea ice cover centre on summer and autumn, when the ice area is particularly low also compared to the ice extent. The recent trends in the Arctic sea ice extent are represented in Fig. 6, in which also the difference (in the linear approximations of the decrease rate) between seasons and annual average is visible. Little ice in summer is usually connected to shorter ice duration: ice both retreats earlier in spring and advances later in autumn. Sea ice duration has regionally (in an area extending from the East Siberian Sea to the western Beaufort Sea) shortened up to 90 ± 16 days between 1979—2011. (IPCC 2013.)

3.5. Future conditions

The changes in the Arctic sea ice cover are known to have feedback effects on the radiative equilibrium. It is estimated that the observed reduction in Arctic sea ice has already contributed approximately 0.1 W m$^{-2}$ of additional global radiative forcing, and that an ice-free summer Arctic Ocean will result in a forcing of about 0.3 W m$^{-2}$ (IPCC 2013). Nevertheless, the Arctic and the changes occurring there have to be assessed in connection with the rest of the world. The Arctic amplification, for example, is not in effect solely an Arctic phenomenon, but a consequence of—or a response to—the interaction between the Arctic and the globe. In other words, the general mechanisms in operation happen to be such that the Arctic seems to respond most severely.

These mechanisms and related interactions have been modeled in order to forecast the most plausible outcomes and to comprehend the consequences of our actions. Below is a very brief account of what present-day modeling is all about. It must be emphasized that such modeling involves vast amount of details which cannot be examined here at length.

In the Fifth Assessment Report (IPCC 2013), the IPCC uses as its main tool the Coupled Model In-
The presence of Arctic amplification is unquestionable in every future projection. On an annual average, and depending on the forcing scenario, the CMIP5 models show a mean Arctic warming between 2.2 and 2.4 times the global average warming (IPCC 2013). The peculiarity of the Arctic is clearly visible in Fig. 8, in which multi-model ensemble averages of surface air temperature change (compared to 1986–2005 base period) for 2046–2065, 2081–2100, 2181–2200 for the four different RCP scenarios (2.6, 4.5, 6.0 and 8.5) are represented. The
Arctic faces the most notable warming in global scale in every scenario.

According to recent studies (Overland et al. 2013), even an Arctic-wide increase of 7 to 13 °C in late fall at the end of the century is possible. The outcomes in question have been gained using RCP scenarios 4.5 and 8.5 (RCP4.5 and RCP8.5), respectively, which means that the increase of 7 °C is likely even though civilization would follow a mitigation scenario and thus cut the emissions notably.

In addition to the forecasting of the average temperatures, also future sea ice conditions in the Arctic have been assessed. The two issues of most interest (and thus catching most attention) are the rates of decrease in the extent of ice on the one hand, and the year in which the ice-free Arctic Ocean realizes on the other. What the ice-free Arctic Ocean means in practice is that the Arctic sea ice extent is less than $1 \times 10^6$ km$^2$ for at least five consecutive years (IPCC 2013). Hence, the approximated year of ice-free Arctic Ocean refers to the year in which Arctic Ocean is nearly ice-free in late summer (that is, in September). Although the discussion about an ice-free Arctic Ocean might thus appear somewhat misleading, even the ice-free conditions in question (that is, less than $1 \times 10^6$ km$^2$ ice extent) constitute a remarkable landmark in the development of the Arctic region in general.

In the Northern Hemisphere, according to the IPCC (2013), the reduction in sea ice extent between the time periods 1986–2005 and 2081–2100 for the CMIP5 multi-model average ranges from 8 % for RCP2.6 to 34 % for RCP8.5 in February and from 43 % for RCP2.6 to 94 % for RCP8.5 in September. Corresponding rates for mean sea ice volume range from 29 % for RCP2.6 to 73 % for RCP8.5 in February and from 54 % for RCP2.6 to 96 % for RCP8.5 in September. In wintertime, the percentages for volume are much higher than the corresponding ones for sea ice extent, which indicates substantial thin-
ning of sea ice. Fig. 9 represents the forecasted trends in sea ice extent in the Northern Hemisphere, and simultaneously illustrates the fact that the models used have rather systematically underestimated the most recent rate of change under all RCP scenarios, especially in September.

The estimates of the year when ice-free Arctic could become reality vary considerably, according to the RCP scenario in question. The year 2050 has been used as a common landmark, and four out of five selected CMIP5-models project a nearly ice-free Arctic Ocean in September before 2050 for RCP8.5 scenario. Fig. 10 visualizes the modeled development of sea ice extent in such high-emission scenario (the horizontal line at $1 \times 10^6$ km$^2$ corresponds to a nearly ice-free Arctic Ocean in September). With more mitigated RCP scenarios the estimates are naturally more restrained. Under RCP4.5, for example, the corresponding year is 2080. (IPCC 2013.)

Considering the situation at the end of the century, according to ESMs, an ice-free Arctic Ocean seems likely. About 90% of the available CMIP5 models reach nearly ice-free conditions during September in the Arctic before 2100 under RCP8.5. The corresponding rate under RCP4.5 is about 45%. Fig. 11 illustrates the possible situation at the end of the century under the two mentioned RCP scenarios (4.5 and 8.5). (IPCC 2013.)

However, as Fig. 9 implied, the current models may underestimate occurring changes. Therefore, even though the emissions would be cut efficiently and thus the radiative forcing of the emissions would be notably constrained, remarkable changes in the ice cover are to be expected.

As there has been rather wide spread in hindcast simulations (the available 23 CMIP5 models produce a range of 4–10 million km$^2$ when simulating sea ice extents for September for the late 20th century under emission scenario RCP 8.5), some culling of the models used in forecasting is reasonable. On these grounds Wang & Overland (2012) have selected a group of seven CMIP5 models, based on observed mean and magnitude of seasonal cycle and an extrapolation approach. For this selection, the interval range for a nearly sea ice-free Arctic is 14 to 36 years, with a median value of 28 years. Put differently, the median value of 28 years related to the base year 2007 implies a loss of Arctic sea ice in the 2030s.

The possible reasons for the apparently unavoidable variation in projections are manifold, and managing them takes considerably time. As the differences between model-based forecasts and observations have decreased but, nevertheless, remained on a significant level, certain caution in drawing definitive conclusions is required. Wang & Overland (2012) thus consider that the models provide only an outer limit for the timing of drastic losses of sea ice, implying that the forthcoming rates of loss may be remarkably greater than the recent forecasts indicate.
4. Shipping in the changing Arctic

As the climate and the sea ice conditions in the Arctic change, the possibilities and the environment of Arctic shipping alter as well. The thinning and retreating of sea ice cover is likely to open up new routes for maritime transportation, both trans- and intra-Arctic. The most significant trans-Arctic possibilities concern the short cut passages between the Atlantic and the Pacific Oceans, either along the northern coast of North America or along the northern coast of Russia. These routes are better known as the Northwest Passage (NWP) and the Northeastern Passage (NEP), respectively. Also more straightforward options right through the Arctic Ocean, up close or across the North Pole, have been considered, but their relevance at present—and presumably in the near future—is fairly minor. The possibility of new intra-Arctic routes relates particularly to an improved access to natural resources, especially oil and natural gas.

The overall decrease of ice cover and the shortening of ice duration may result in an increased access to certain areas in the Arctic region, but the occurring changes will be manifold and involve more dimensions than mere benefits to maritime transportation. The major implications comprise at least of alterations in weather and marine conditions, different behavior of glaciers and hummocks, and the consequences of ever larger fleet with varying standards of equipment being exposed to the harsh conditions of the Arctic. In addition, there are the increased emissions, which distribute geographically in a new and thus unforeseen way. The constitution and the possible meaning of these emissions will be discussed in detail later on (in section 5), and merely the other, somewhat more straightforward aspects are examined here.

4.1. Influences caused by changing climate and sea ice conditions

In general, apart from the influence on feedback mechanisms (see section 3.2), the loss of sea ice is likely to alter regional weather and marine conditions. Enhanced atmospheric humidity and cloudiness are to be expected, as well as changes in upper-ocean stratification, and ocean temperature and salinity near the surface (ACIA 2005). Especially summer fogs will become more common (DNV 2010). Also, as there will be less sea ice to dampen the waves, more attention to wave heights and directions will be needed (AMSA 2009). Harsher wind conditions and higher waves will in turn lead to more sea spray and to the consequent icing of vessels (DNV 2010). In addition, the count and the intensity of low-pressure systems (polar lows) are likely to increase (ACIA 2005). All in all, the decrease of sea ice cover makes the weather and maritime conditions more unforeseeable, and forecasting becomes more difficult.

Concerning the behavior of glaciers and hummocks, the warming of the Arctic climate will lead to the shattering of the structure of ice. In other words, more calving and thus an increased number of smaller icebergs are to be expected (DNV 2010). These icebergs, especially in conjunction with the increased fog in summer, pose a significant threat to shipping activities.

It is thus noteworthy that the maritime conditions even in the so-called ice-free state of the Arctic Ocean pose remarkable challenges and difficulties to transportation activities. As mentioned before, an ice-free Arctic refers to the situation in which the Arctic sea ice extent is less than $1 \times 10^6$ km$^2$, ice extent being defined as the sum of ice covered areas with concentrations of at least 15%. Securing safe operation in such conditions undoubtedly demands extra care and investments. In addition, as the regulation of operation in the Arctic is yet rather low and insufficient, inappropriate equipment and preparations may comprise a serious issue in the Arctic conditions (AMSA 2009). These issues will be discussed in detail later on (in section 4.5).

4.2. The possible shipping potential in the Arctic: why the Arctic is so attractive?

The decrease of the Arctic sea ice is likely to open up new possible routes and regions for maritime activities; both trans- and intra-Arctic dimensions involve notable potential. Trans-Arctic shipping refers
mainly to the possibility of sailing along the northern coast of either North America or Russia instead of using traditional routes via Suez or Panama Canal. By choosing an Arctic transit route major savings in travel distance and time can be gained, at least in principle. Intra-Arctic or destination shipping (that is, shipping to and/or from an Arctic destination), in turn, consists of petroleum and mineral extraction related marine activities, fishery, local community re-supply, and tourism. (AMSA 2009.)

4.2.1. Trans-Arctic passages

Despite of the comparatively evident advantages the new routes seem to entail, some questions of considerable importance request further attention. Distance savings, when comparing trans-Arctic and traditional routes, can be up to 50% (see Fig. 12) (Ragner 2000). For example, the distance between Rotterdam and Yokohama is about 11,200 nautical miles using the route via Suez Canal, compared to the 6,500 nautical mile route across the top of the world (AMSA 2009). As the distance traveled becomes shorter, fuel consumption and thus emissions decrease in proportion. Hence, there is significant potential for cost savings, arising from both direct (reduced fuel cost and lower inventory-holding costs) and indirect factors (the cost of emissions due to environmental protection taxes) (DNV 2010).

However, a saving of certain percentage in distance does not entail a corresponding saving in time, since the short cut option may involve notable challenges and obstacles that hinder the journey. The occurrence of sea ice, for example, is likely to cause decrease in travel speed, even though it would not pose immediate danger to the vessel. Likewise, the reduction in fuel consumption is not necessarily proportional to the saving in distance, as higher output power is needed in heavy ice conditions (that is, when the vessel has to break sea ice and/or push it away). (DNV 2010.)

The different projections concerning the future development of various trans-Arctic passages are further assessed in section 4.4.

4.2.2. Oil and gas

The role of the Arctic as a relevant natural resource repository depends in part on the development of sea ice cover. Improving access to remote reserves of oil and natural gas in the Arctic may lead to notable revisions of strategies concerning petroleum activities, since the Arctic is estimated to contain as much one-fifth of world’s undiscovered oil and natural gas (AMSA 2009). The more exact numbers are 90 billion barrels of oil, 1,669 trillion cubic feet (47 trillion cubic meters) of natural gas, and 44 billion barrels of natural gas liquids (USGS 2008).
There are notable differences in the geographical distribution of the Arctic oil and gas. For gas, Arctic Russia dominates clearly with about 70% of total arctic resources; for oil, the situation is more balanced, even though Arctic Russia still has the largest share (41%) (Lindholt & Glomsrød 2011). Fig. 13 illustrates the regional distribution of undiscovered oil and gas in detail. While the dominance of Russia in this regard is rather clear, the shares concerning undiscovered petroleum resources still differ notably from those concerning proved reserves: Russia’s share of proved oil and gas reserves in the Arctic are overwhelming 90.2% and 98.6%, respectively (Østreng et al. 2013).

Although the presence of relatively large resources does not itself tell much about the possibilities and the schedules of either discovery or utilization\(^3\), some conclusions based on the location of the reserves can be drawn. Apart from the forthcoming changes in petroleum related transit routes, the retreat of sea ice has additional relevance, as it is estimated that approximately 84 percent of the undiscovered

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\(^3\) The reasons for such uncertainty have above all financial basis, since the utilization of Arctic resources has thus far remained fairly expensive compared to the level of costs in more favorable environments. For example, it has been estimated that the cost of drilling an onshore well is approximately 540% higher in the Arctic than in the US as a whole. With regard to offshore wells, the expenses may be up to 760% higher. (Østreng et al. 2013.)
oil and gas occurs offshore (USGS 2008), and the resources located in either ice-free or seasonal ice-free areas require modifications of technology only instead of totally new solutions (Lindholt & Glomsrød 2011).

The estimates of forthcoming intra-Arctic oil and gas production rates vary considerably. These estimations rely on global scale models concerning overall oil and gas production, and the actual share the Arctic is likely to have (Peters et al. 2011). One such modeling tool is Framework of International Strategic Behaviour in Energy and Environment (FRISBEE), which “describes future supply and demand of oil and gas through elaborate modeling of oil and gas investments and production” (Peters et al. 2010). The emphasis of the model is on petroleum markets, but also the global market for coal and regional markets for electricity are modelled, although in less detail (Lindholt & Glomsrød 2011).

Even though based on the same modeling tool (FRISBEE), different analyses have led to differing results. It must be noted that the world market price of oil is exogenous in the model, as there are powerful actors (such as OPEC) in the oil production scene that for their part define the price level (Lindholt & Glomsrød 2011). Thus the different oil world market price levels as model inputs produce various outcomes, but this does not seem to explain the variation entirely. Such is the case, for example, when comparing outcomes of Peters et al. (2011) and Lindholt & Glomsrød (2011), of which both use FRISBEE.

Both analyses include scenarios with varying levels of oil price, and they both aim at modeling the rates of oil and gas production in the Arctic as a function of two different variables—that is, the world market price of oil, and time. The results are similar but not identical; Fig. 14 illustrates some central findings. The inconsistencies discovered will not be discussed here in detail, but a significant difference in the role of Greenland is yet noteworthy.

4.2.3. Minerals

In addition to oil and gas, there are other natural resources in the Arctic that will be easier to utilize as the sea ice cover diminishes. From a global perspective, the absolute number of current mining operations in the Arctic is small; out of the approximate 25 000 industrial mines worldwide probably fewer than 50 are located north of the Arctic Circle (Andrew 2014). Nevertheless, the extraction of hard minerals in the Arctic is of remarkable magnitude, for the largest zinc mine in the world (Red Dog in the Alaska Arctic) and the largest nickel mine (Norilsk in Siberia) are located there; they both are solely dependent on marine transport systems, and the shortening of sea ice duration may improve their existing access significantly (AMSA 2009).

The Mary River iron ore deposits on Baffin Island, Nunavut in the Canadian Arctic represent a highly valuable mineral resource. The development of mining operations has been planned for some time, and the objectives are rather ambitious: approximately 18 million tons of ore per year will be shipped to European markets, with the operations spanning at least 25 years. In Greenland, the Kvanefjeld Project represents a multi-element deposit containing rare elements, uranium and sodium fluoride. Other potentially world class and multi-commodity ore deposits exist in coastal Greenland. The exploration and development of these mines depends largely on Arctic marine transport systems, as shipping comprises the only sensible way to carry these scarce commodities to global markets. (AMSA 2009.)

4.2.4. Fishery

In a global scale, Arctic fisheries comprise an area of moderate importance (Østreng et al. 2013). From the perspective of Arctic shipping, fishing vessel operations constitute a significant portion of all vessel activity (AMSA 2009). Four marine ecosystems dominate the fishery scene, namely the Northeast Atlantic (the Barents and Norwegian Seas), the Central North Atlantic (the waters around Iceland, the Faroe Islands and East Greenland), the waters off North-eastern Canada (Newfoundland and the Labrador area), and the Bering Sea (Østreng et al. 2013). Fishing vessel activity, however, takes mainly place in a few major locations, including the Bering and Barents seas, the west coast of Greenland, and the surroundings of Iceland and the Faroe Islands (AMSA 2009).
Since fishing is possible in areas that are either completely or seasonally ice-free (that is, in areas that have at most low ice concentration), the development of the Arctic sea ice extent has considerable significance regarding the future of Arctic fishery (AMSA 2009). In addition, due to the warming of the climate some fish stocks with notable economic bearing, such as cod and herring, may become more plentiful in the Arctic waters in the future (Østreng et al. 2013). Higher temperatures and reduced ice cover may improve conditions for these particular fish stocks and thus lead to increase in productivity, but the consequences of the climate change for fishery are not merely positive, as some other species lose their natural habitat (Østreng et al. 2013).

4.2.5. Local community re-supply

In the Arctic, there is a notable amount of communities with very limited access to essential supplies, and appropriate re-supply must be arranged. “Re-supply activities provide a lifeline to many communities that have no or very limited road access and no or limited capacity to handle heavy aircraft; most communities serviced are ice-locked for parts of the year and rely heavily on marine transportation during the summer months for their dry foods, fuel, building materials and other commodities” (AMSA 2009, 75). Such communities are thus very dependent on external services, which are commonly provided by assistance of shipping.

As community re-supply in the Arctic is expected to expand due both to population increases and increasing development in the region, more weight is added also to the execution of functional and appropriate maritime activities. Along the improving access via ice-free sea routes, the increasing demand for goods and construction materials may be more effectively fulfilled in the future. (AMSA 2009.)

However, as sea ice cover is decreasing and permafrost on land areas is thawing, possibilities for traveling over sea ice and over land get worse. Changing maritime conditions can make the traveling by boat more dangerous or even impossible in some coastal areas, whereas the vanishing of ice roads and roads built on permafrost can hinder land-based transportation, possibly leading to isolation of certain areas (see Fig. 15). Some of the lost connections may be replaced by new shipping routes, but not all. In any case, the dependence on externally provided maritime transportation is likely to increase, reducing the level of self-sufficiency of remote communities. (AMAP 2011b.)

4.2.6. Tourism

Tourism comprises the most of all Arctic passenger vessel activities, and marine-based tourism is the largest segment of the Arctic tourism industry. The size and the type of passenger vessels used vary according to the primary function of the vessel and the primary area of operation. However, nearly all passenger vessel activity in the Arctic takes place in ice-free waters and in the summer season. Fig. 16 illustrates the geographical distribution of passenger vessel journeys in 2004. (AMSA 2009.)

Arctic tourism is predicted to grow along the disappearance of major barriers, such as physical in-accessibility, lack of infrastructure, poor regulations, high costs, and large travel distance (Andrew 2014). Cruise ship traffic in the Arctic region has already increased significantly, also in the short run:
the amount of 1.2 million passengers in 2004 traveling to Arctic destinations aboard cruise ships had by 2007 more than doubled (AMSA 2009).

Tourism-related economic benefits in the Arctic are likely to be rather insignificant, at least when compared to the scale of increased resource extraction, whereas substantial negative impacts may yet occur, as potential environmental hazards and the providing of adequate search and rescue services cause notable expenditures (Andrew 2014). Many of the cruise vessels traveling to Arctic destinations may not be appropriately ice-strengthened, as the growing demand exceeds the capacity of vessels constructed or designed to operate in Arctic conditions, which in conjunction with the undersized emergency response capabilities of local communities pose a remarkable risk of humanitarian disaster (AMSA 2009).

4.3. Questions of governance—regional sovereignty and global power constellations

4.3.1. Regional sovereignty and the extent of local governance

As Andrew (2014) has pointed out, the development of the Arctic has a significant role concerning also the sovereignty and governance of certain regions. The possibility of the utilization of previously untouched natural resources has made visible the questions about how managing the related risks and gaining the benefits are eventually connected. As the most remarkable risks (environmental, social, etc.) are local by nature, the demand for profiting the local communities is in principle justified. In some cases, relatively independent regional governance is seen as a necessary prerequisite for securing the local benefit. Such pursuits of sovereignty have occurred especially in Greenland and Nunavut.

Yet it is not clear, whether the local governance secures the benefit of both the people and the environment in the best possible way. In Greenland, for example, a ban on mining radioactive materials, originally put in place by the Danes, has been abandoned; Nunavut, for its part, has adopted business-friendly regulations which include low tax rates and streamlined processes (Andrew 2014). It remains to be seen how low the level of control is going to be and what the consequences of such policies eventually are. It is reasonable, however, to ensure by international laws and agreements that the local governments and other decision-making bodies will not get blinded by the opening of grandiose financial opportunities.
4.3.2. An “industrial Mediterranean”

Apart from the questions of sovereignty, there are governance-related disputes of even greater magnitude in the Arctic. As the Arctic comprises an area with remarkable geopolitical significance, it in part functions as a stage of global power constellation. The geopolitical significance of Arctic arises particularly from its geographical location between three of the most industrialized and developed continents of the world (that is, Asia, Europe and North America) and its assumed abundance of strategically important industrial resources and mineral deposits (Østreng et al. 2013). For example, about 80% of the world’s industrial production takes place north of 30°N latitude, and thus the Arctic Ocean is actually an “industrial Mediterranean”, as Østreng et al. (2013) put it.

The central location of the Arctic may have remained somewhat obscure partly because of the established methods of map-making and picturing the world, as the Arctic is usually placed at the top of the world. The Arctic is thus easily conceived as a rather remote area, and the Arctic Ocean may get categorized as distant and precarious waters (for more about the interpretation and comprehension of maps, see Short 2003).

To be sure, there are adequate reasons for the relatively low level of interest concerning the Arctic, too. First and foremost, the overall climate and maritime conditions have posed remarkable challenges and threats to all kinds of operations in the Arctic, thus making it distant and occasionally even inaccessible. Hereby the distance connected with the Arctic is, for the most part, operational—not so much geographical.

4.3.3. Actors in the Arctic

Now that the operational conditions in the Arctic are changing to a slightly more favorable direction, the status of the Arctic will be reassessed. The overall development of the Arctic is, apart from natural conditions, a question of politics and exercise of power. Thus, different political actors (that is, single nation states, coalitions, councils, etc.) on their part define the future in the Arctic, and various interests and incentives drive the forthcoming actions.

Among the Arctic related actors there are more and less powerful single nation states, and more and less extensive groupings that comprise of single nation states. The parties involved can be grouped in numerous ways, for example according to size, geographical location, or overall activity in the Arctic. One essential method of sorting is whether the party has direct geographical connection to the Arctic or not. Hence the geographical definition of the Arctic region is of much importance, and some disputes in relation to the extent of the Arctic region have occurred rather recently. For example, the Arctic connections of three Nordic countries—namely Finland, Iceland and Sweden—have in certain contexts been questioned. Such exclusion politics have at times been promoted by appealing to the importance of cooperation between the coastal states of the Arctic Ocean when discussing, for instance, new ways of thinking about regional economic development and environmental protection. (Østreng et al. 2013.)

The Arctic council is the most important intergovernmental forum on which Arctic issues are addressed. The council has eight member countries (Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the United States) of which six are Arctic coastal states. The council has a rather limited mandate of environmental protection and sustainable development, but its role with regard to the future of Arctic region may be considerable, depending partly on the outlook of its most powerful member states. (Østreng et al. 2013.)

Although Arctic issues involve very many directions altogether, the number of participants in decisive councils managing the most acute concerns is usually kept limited by the organizing parties. Such alignments are, however, always multidimensional: inclusive consultations allow comprehensive and profound discussions on the one hand, but the presence of somewhat non-affected and thus extra parties may complicate negotiations and delay resolution on the other. (Østreng et al. 2013.)

Even if the main goals (that is, securing peace and conditions for international cooperation while utilizing natural resources in an environmentally sustainable way) concerning the Arctic are consistent among the different parties, they nevertheless exercise various Arctic strategies according to their resources and assets, and the overall position they occupy in the larger context. This applies to the attitudes of the parties towards collaborating and the international law as well, as the possibilities for acting alone are typically very limited, especially for small parties. (Østreng et al. 2013.)
As Østreng et al. (2013) note, small parties “benefit the most from a collaborative atmosphere, [and] in this perspective, they are the most likely and prone to seek political adjustment, compromise, alliance building and mitigation within the framework of international law.” Although the first line of action, shared with everyone, is to act peacefully and in cooperation with others, big parties have better abilities to exert power, and thus to shape international relations to the best of their own idiosyncratic interest (Østreng et al. 2013).

4.3.4. The governance of Arctic shipping

The timeliest global-scale questions of governance in the Arctic relate to the administrative status of the trans-Arctic passages: either the jurisdictional status of the passage is unclear or the principles of applied national administrative authority are found difficult and disadvantageous. On the one hand, the primary littoral state the Northwestern Passage (that is, Canada) regards the passage as being partly located inside its national boundaries—and thus as its internal waters—whereas other parties see the situation rather differently. On the other hand, the littoral state of Northeastern Passage (that is, Russia) has, for its part, used its undisputed legal authority over its territorial waters in a way that may have hindered the full international utilization of the shipping route.

The corresponding rights of the littoral states (of both internal waters and other maritime zones) are based on the Law of Sea, which “as reflected in the 1982 United Nations Convention on the Law of the Sea (UNCLOS), sets out the legal framework for the regulation of shipping according to maritime zones of jurisdiction” (AMSA 2009). The extent of legislative and enforcement control over foreign ships by the coastal states varies according to the different maritime zones set out in UNCLOS, and is greatest for internal waters, where coastal state’s sovereignty equals that of its land territory (Østreng et al. 2013). In other words, a foreign ship desiring to enter internal waters will need permission from the coastal state in question (Østreng et al. 2013).

Territorial seas comprise the area adjacent to internal waters, reaching up to the limit of 12 nautical miles from the coastline. Here foreign ships have the right to innocent passage, but the role of the coastal state remains strong. The status of territorial seas is described as follows: “UNCLOS allows coastal states the authority to adopt laws and regulations applicable to foreign ships transiting through the territorial sea. Domestic laws can be applied in relation to such things as safety of navigation, preservation of the marine environment and marine pollution control.” (AMSA 2009.) In addition, coastal states have no right to charge the passage of its territorial seas itself, but specific fees for provided services may be charged fairly and without discrimination. (AMSA 2009.)

In its exclusive economic zone (EEZ; 200 nautical miles measured from the territorial sea boundaries), a coastal state has sovereign rights to explore, exploit, conserve and manage its natural resources, and pose legal regulations over such things as protection of the marine environment. The EEZs have some additional significance in the Arctic, as the article 234 of UNCLOS “recognizes the coastal state’s right to adopt and enforce special non-discriminatory pollution prevention, reduction and control laws in areas within the limits of the EEZ that are covered by ice for most of the year, when certain conditions are met” (AMSA 2009). The coastal states of the Arctic Ocean have thus certain broadened authority reaching about 400 km offshore, but the exact meaning of the UNCLOS article 234 varies according to the interpretation, leaving notable obscurity in the extent of coastal state’s regulatory power. (AMSA 2009.)

Against such jurisdictional background it is understandable that the situation concerning the Arctic passages has become tense. As Canada claims that the NWP partly comprises of its internal waters, it at the same time tries to maintain the most extensive regulatory authority, including the right to deny access to the waters in an extreme situation. Canada’s outlook has not been approved broadly: both the US and the EU demand non-regulated transit, claiming that the passage represents international straits (Andrew 2014). In principle, UNCLOS sets forth the rules on setting boundaries for internal waters, but apparently there is some confusion among definitions, as the situation remains unsettled (AMSA 2009).

Concerning the situation of the NEP and Russian coastal waters, “Russian authorities have made it clear that navigating along these waterways must be conducted in accordance with provisions laid down in Federal Russian law” (Østreng et al. 2013). There are appropriate grounds for such view, especially as the UNCLOS article 234 notably expands the regulatory rights of the Arctic coastal states. The even-
tual extent of the coastal state’s authority and the appropriateness of the related provisions, however, have given rise to disagreements and disputes.

Customarily, a prior inspection in a Russian port and icebreaker assistance in certain areas have been obligatory requirements for transit. Recently, these regulations have been abandoned, and the determination of icebreaker assistance fees has been clarified, so that the payment corresponds to actual services rendered—not to operator’s paying potential. Despite this, the regulation of the navigation along the NEP has remained on a rather high level, mostly due to the extensive advance reporting and the applications for transit permission the Russian authorities demand. These issues, in conjunction with the fairly high icebreaker assistance fees, have likely contributed to the relatively low share of international vessels using the NEP. (NVP 2013.)

4.4. How Arctic shipping may evolve?

The possibilities concerning the development of Arctic shipping have been forecasted using different modeling methods and presuppositions, and special emphasis has been laid on various aspects. The most central questions within such forecasting involve the development of sea ice conditions, the overall profitability of alternative routes, and the emissions caused by shipping. The outcomes of projected developments depend crucially on the theoretical models used and the general assumptions made; hence critical and even cautious approach is advisable.

In addition to important the climatic factors (that is, for example, how the sea ice extent and the general maritime conditions will develop), there are socio-cultural, financial, technological and political issues that for their part determine the future possibilities of maritime activities in the Arctic waters. The eventual real-life progression is a complex sum of the interaction between all these aspects, but due to technical limitations in modeling, an all-inclusive analysis is in effect impossible.

Hence, manifold projections, focusing on different aspects and utilizing various data, have been used to outline possible future scenarios. The main goal of such projections is thus not so much to describe forthcoming development in detail and as accurately as possible, as to illustrate the scope of possible directions regarding future development. The emphasis is on the overall situation and relevant consequences, and particular storylines are used as a heuristic framework.

To be more specific, the most significant practical non-climatical factors influencing the future of shipping in the Arctic include the development of global maritime industry, the feasibility and the world market prices of natural resources, and the implementation of relevant environmental policies. These issues comprise the overall context in which Arctic shipping will evolve, and even a rather minor turn in any of them might alter the situation in the Arctic remarkably.

In this section, a few elementary Arctic-specific scenario based projections are presented. These projections give a general view of what the future Arctic might look like and what kind of possibilities for shipping there might exist. In the next section (that is, section 5), more notice of current and future emissions and their possible climate impacts is taken.

4.4.1. The AMSA scenarios: an overview on the Arctic development

The AMSA (2009) scenarios comprise a very broad view of what the future Arctic might look like. The overall focus of the AMSA is marine safety and marine environmental protection, and thus these issues for their part define the formulation of different AMSA scenarios. An increasing interest in developing Arctic natural resources and the related transformation of marine activity in the Arctic, in conjunction with regional climate change and the resulting Arctic sea ice retreat providing for increased marine access comprise the grounds for the AMSA scenarios. The main function of such scenarios is to help “understand more clearly the uncertainties that might shed light on the determinants of future Arctic marine operations” (AMSA 2009, 92).

Two primary drivers and key uncertainties were selected as the axes of uncertainty for the final AMSA scenario matrix. The two most determining and yet separate enough factors are Resource and Trade on the one hand, and Governance on the other. Resource and Trade refers to “the level of demand for Arctic natural resources and trade”, whereas Governance consists of “the degree of relative stability of rules for marine use both within the Arctic and internationally” (AMSA 2009, 94).
These crossed uncertainties (that is, Resources & Trade and Governance) produce four different scenarios which all examine a variety of possible factors concerning the development of the Arctic. The outcomes are named as Arctic Race, Polar Lows, Polar Preserve, and Arctic Saga. The Arctic Race is a combination of a high level of Resources & Trade and a low level of Governance, whereas the Polar Lows comprises of a low level of Governance combined with a low level of Resources & Trade. In both Polar Preserve and Arctic Saga scenarios the level of Governance is high, but in the first the level of Resources & Trade is low and in the latter it is high. The detailed contents of each scenario are shown in Table 1. (AMSA 2009.)

The AMSA scenarios work discusses a multitude of questions related to Arctic shipping, but some particular issues are highlighted. Special notice is given first to the globalization of the Arctic, taking place through the increasing natural resource extraction and the corresponding marine traffic in the Arctic. Second, the arrival of the global maritime industry in the Arctic Ocean is likely to have notable ef-

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Table 1. The detailed contents of the four AMSA scenarios. Source: AMSA 2009.
fects, as the amount of trans- and intra-Arctic voyages of large tankers, cruise ships and bulk carriers increases. Third, in addition to the overall increase in maritime activities, there is a remarkable lack of international policies. As a consequence, the maritime governance is rather challenging and insufficient, leaving both the related people (local residents, maritime workers, etc.) and the environment vulnerable to possible threats. (AMSA 2009.)

4.4.2. Projections of Arctic shipping: possible new routes for growing maritime industry

The above-mentioned AMSA work has become a kind of landmark in studies concerning Arctic shipping. It has gained status as a significant reference, and it has been widely utilized in subsequent examinations. The AMSA both provides a large amount of detailed knowledge and in part sets the framework for future research, as subsequent articles and other publications are usually positioned in relation to the AMSA.

One notable example of the research based on the AMSA more directly is the article of Corbett et al. (2010). It examines quantitatively the future emissions of growing marine transportation in the Arctic, thus exceeding the proper scope of the AMSA, but it nevertheless relies on the empirical data of shipping activity produced in the AMSA work. On the grounds of these data and an additional analysis concerning the development of shipping in the Arctic, an assessment of future Arctic emissions in multiple scenarios is presented. (Corbett et al. 2010.)

In assessing the extent of forthcoming Arctic maritime activities, Corbett et al. (2010) utilize the global evaluation of shipping provided by International Maritime Organization (Buhaug 2009). The IMO study in question is based on an exhaustive analysis of both historic correlation between global GDP and demand for sea transport, and more detailed interconnections between developments in trade, locations of factories, consumption of raw materials, changing trade patterns, and possible new sea routes. As an outcome of this account, an estimation of future levels of global demand (in tonne-miles) with plausible upper and lower boundaries is gained. Corresponding annual growth rates are also calculated.

On the grounds of IMO study, Corbett et al. define two parallel scenarios with different rates for in-Arctic growth and trans-Arctic diversions, namely the Business As Usual (BAU) and High Growth (HiG) scenarios. The BAU scenario comprises of a moderate increase in the maritime activities, whereas the HiG scenario the Arctic faces remarkable change in shipping, posing also notable challenges and threats to the people and the environment. Also the role of the Suez and Panama Canals is considered when assessing the feasibility of Arctic shipping. (Corbett et al. 2010.)

Table 2. The in-Arctic growth rates by vessel type used in Corbett et al. (2010) projections. Source: Corbett et al. 2010.
Corbett et al. presume an annual growth in global shipping activity \(^4\) of 2.1% for the BAU, and of 3.3% for the HiG scenario. Due to the retreating sea ice cover and the corresponding opening of new trans-Arctic routes, a certain amount of diversion traffic via the Arctic Ocean is expected, according to the scenario in question (1%, 1% and 1.8% (BAU), or 1%, 2%, and 5% (HiG) of global shipping for 2020, 2030, and 2050, respectively). The corresponding in-Arctic growth rates by vessel type are presented in Table 2. (Corbett et al. 2010.)

With regard to in-Arctic shipping, the asymmetric growth in activity among ship types is taken into account. For example, the vessel activity involved in moving containerized goods and energy products is growing at a faster rate than other ship types. On the other hand, even though fishing vessels constitute a significant portion of all vessel traffic in the Arctic regions at present, they are excluded from the Corbett et al. assessment due to methodological reasons. (Corbett et al. 2010.)

Altogether four trans-Arctic routes are proposed, and their operability is reported by approximating rather roughly the share of trans-Arctic passages each route might hold in future. The routes are identified as Northeast Passage (NEP), Northwest Passage (NWP), Western Polar Route (WPR), and Eastern Polar Route (EPR). The geographical locations of the routes are illustrated in Fig. 17, and relevant details are presented in Table 3. (Corbett et al. 2010.)

Table 3. Details of certain essential assumptions underlying the Corbett et al. (2010) projections: the share of global shipping diverted, the length of navigation season on the diversion routes, and the relative distribution of the diverted traffic on the alternative routes. Source: Corbett et al. 2010.

<table>
<thead>
<tr>
<th>Year</th>
<th>Global Shipping Diverted</th>
<th>Diversion Months</th>
<th>NEP</th>
<th>NWP</th>
<th>EPR</th>
<th>WPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010–2020</td>
<td>1%</td>
<td>Aug, Sep, Oct</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2020–2030</td>
<td>2%</td>
<td>Aug, Sep, Oct</td>
<td>50%</td>
<td>50%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>2031–2040</td>
<td>3.5%</td>
<td>Jul, Aug, Sep, Oct</td>
<td>40%</td>
<td>40%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>2041–2050</td>
<td>5%</td>
<td>Jul, Aug, Sep, Oct, Nov</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
</tr>
</tbody>
</table>

\(^4\) The eventual increase in shipping activity (traveled distance, mileage) results from the growth of total transport volume (expressed in tonne-miles). If the average load of vessels is presumed to remain unaltered, the traveled distance increases proportionally to the total transport volume. The increase in traveled distance in turn leads to corresponding growth in fuel consumption and thus in emissions.
According to Corbett et al., the High-Growth scenario somewhat resembles the AMSA scenarios with a high level of Resources & Trade, namely the Arctic Race and the Arctic Saga. However, no direct comment on the level of Governance is given, though different emission scenarios with respect to the implementation of reduction technologies are yet presented (these will be discussed in section 5). (Corbett et al. 2010.)

4.4.3. Focus on feasibility and economy

DNV (2010) has presented another, more technical and economic assessment concerning the feasibility of future Arctic shipping. In this study, the likely forthcoming sea ice conditions are used as basis for the analysis, and the possibility of increase in Arctic maritime activities is evaluated against such background. In other words, the usage of trans-Arctic passages must be both technically and economically justifiable, and this sets the definite framework for all future development.

From the perspective of DNV’s study, sea ice conditions and its consequences to vessel speed and fuel consumption are questions of essential significance. Thick ice reduces the speed and increases the fuel consumption, thus making the navigation less profitable. Thick enough ice halts the vessel and prevents the intended transition through ice cover. In addition to these key aspects, some other factors such as safety, risk managing and reliability with respect to transit time are taken into account. (DNV 2010.)

The analysis includes a projection of future ice concentration and thickness for the years 2007-2100, which is gained by using the Community Climate System Model (CCSM3) developed by National Center for Atmospheric Research (NCAR). The underlying emission scenario is SRES A2; a scenario with modest reductions in CO2 emissions compared with “business as usual”. (DNV 2010.)

Four trans-Arctic route options are considered, all of which centre around the NEP and the Russian coast. Based on route distance and predicted ice conditions, one particular route is singled out for further study. Above all, vessel speed and fuel consumption are examined as a function of vessel’s geographical location. The evaluation relies on the predicted sea ice conditions in 2030; thus possible inaccuracies in modeling the ice cover will directly alter the outcome. The applied projections of ice conditions in 2030 (both in winter and in summer), corresponding vessel speed, and vessel fuel consumption for the selected route (for a 6500 Twenty-foot Equivalent Unit (TEU) container ship with bulbous bow) are presented in Fig. 18. The illustration clearly spots the critical parts of the transfer journey; here the ice conditions are likely to remain particularly challenging in the near future. (DNV 2010.)

Based on the above-described assessment considering the possibilities of trans-Arctic shipping, an economic analysis is carried out. For these purposes, future Asia—Europe cargo volumes are estimated

![Fig. 18. The projections of ice conditions in 2030 (in winter and in summer; left-hand images), corresponding vessel speed (center image), and vessel fuel consumption (right-hand image) for the examined route (for a 6500 Twenty-foot Equivalent Unit (TEU) container ship with bulbous bow) from the DNV (2010) analysis. In the speed graph red indicates unreachable areas (speed is zero), whereas blue denotes ice-free conditions (normal cruising speed). In the fuel consumption graph red sections indicate increased fuel consumption (due to heavy ice conditions). Source: DNV 2010.](image-url)
by translating the IPCC A2 scenario projections for global economic development into global seaborne trade volumes. Applied estimates rely solely on the strong historical correlation between Gross Domestic Product and seaborne trade, but considering the likely development of the world economy, the Asia—Europe trade increase was assumed to be lower than that of global trade. Thus the Asia—Europe trade volume is assumed to grow by 40% from 2006 to 2030 and by 100% from 2006 to 2050, corresponding to total trade potentials of 3.9 million TEU and 5.6 million TEU, respectively. (DNV 2010.)

For the modeling purposes, all future Asia–Europe traffic is represented by trade between hubs, which represent a wider geographical area. One European hub (Rotterdam) and three Asian hubs (Tokyo, Hong Kong and Singapore) are taken into consideration, and the cargo volumes are assumed to be split equally between the three Asian hubs. Two different scenarios for shipping are examined: an all-year Arctic operation of 5000 TEU double-acting container vessels, and summer operation of 6500 TEU PC4 ice-classed container vessels. The fuel costs, expenses from transiting through ice, and additional investments for ice strengthening are included in the cost calculations. The bunker prices are assumed to be $600 per tonne in 2030 and $750 per tonne in 2050. (DNV 2010.)

According to results of DNV’s evaluation, Arctic transit will be economically attractive for part-year container traffic from the Tokyo hub in 2030 and 2050. Of the projected total trade potential of 3.9 million TEU from the Tokyo hub in 2030, 1.4 million TEU is estimated to be transported across the Arctic. This amounts to a total of about 480 transit voyages across the Arctic in the summer of 2030. For 2050, the corresponding rates are 2.5 out of 5.6 million TEU, resulting in 850 passages. These amounts imply that a share of about 8% of the total container trade between Asia and Europe in 2030 is transported via Arctic, increasing to about 10% in 2050. (DNV 2010.)

The feasibility of trans-Arctic passages is not solely a function of the vessel’s speed, duration of ice-free conditions, bunker prices and the overall development of world economy, but it also depends on the possible icebreaker assistance and transit fees, investments in equipment and personnel training, and insurance costs. From this perspective, DNV’s analysis is fairly narrow-scoped and thus illustrates the overall situation only in part and rather incompletely. As the feasibility of Arctic transit routes is a function of so many factors and the underlying mechanisms are undoubtedly manifold, an all-inclusive assessment may seem impossible. Even though subsuming all these possible variables into one modeling tool may comprise an overwhelming task, some sensitivity analyses can be executed. This way, even slightly deeper understanding of the undeniably complex totality is attainable.

Liu & Kronbak (2010) have examined the feasibility of Northern Sea Route (NSR), using bunker prices, navigation season length and icebreaking service fees as their explicit variables. They have also paid attention to costs related equipment and crew, repairs and maintenance, and insurances, though the emphasis of their analysis is on the three above-mentioned main variables. The route under scrutiny is between Rotterdam and Yokohama, and the trans-Arctic option is assessed in comparison with the traditional route via Suez Canal. Corresponding total sailing distances are 7100 and 11400 nautical miles (M), respectively. The examination concerns 4300 TEU container ships, either with or without ice-strengthening.

Liu & Kronbak have, however, divided the trans-Arctic route—that is, the NSR—to ice-free and ice covered portions, both having appropriate and separately evaluated rates of average sailing speed and fuel consumption. The distances of ice-free and ice covered portions are assumed to vary according to the length of navigation season, thus comprising the total of 7100 M with different relative proportions. By varying the length of ice covered portion of the route, the general significance and the presumable hindering effects of the ice cover can be highlighted. Altogether three navigation season lengths (3, 6 and 9 months) and the corresponding distances covered with ice (700, 300 and 100 M, respectively) are included in the study. (Liu & Kronbak 2010.)
The icebreaking assistance fees in the NSR have fluctuated, and the future development is uncertain. Nevertheless, the current prices are generally considered to be so high that the icebreaking related expenses hinder the utilization of the NSR remarkably. Hence only projections involving a reduction in the fees are included in the study, and three different levels of reduction (50 %, 85 % and 100 %) and their corresponding effects are examined. Also three different bunkers prices (350, 700 and 900 USD per ton) have been considered, representing various possible oil world-market futures. A constant freight rate of $1200 per TEU is applied, so that the effects of altering expenses are neglected. (Liu & Kronbak 2010.)

The results of Liu & Kronbak are illustrative in presenting the significance of both icebreaking fees and the bunker prices. According to the study, the transit via NSR is not profitable in any future scenario with current icebreaking fees. However, with a reduction of 50 % in icebreaking fees, few profitable options utilizing the NSR eventually exist. Furthermore, with a reduction of 85 %, the NSR becomes economically competitive with the traditional Suez Canal route. Such development is bolstered by the reduction of 100 %. (Liu & Kronbak 2010.)

Perhaps the most interesting observation is nevertheless related to the effects of bunker prices, as the Suez Canal route is profitable only with the lowest price (350 USD per ton), but already with a bunker price of 700 USD per ton a few NSR options are profitable (with assumed elongated navigation season and reduced icebreaking fees). With the highest bunker price (900 USD per ton), the NSR option with the longest navigation season and free icebreaking services is the only one that reaches to profit. In other words, if the bunker prices begin to soar due to the world-market situation, the NSR may at least be a reasonable route option—if not the only profitable one. Fig. 19 represents the profitability of different options as a function of bunker price and navigation season length (with a constant reduction of 85 % in icebreaking fees) on the one hand, and as a function of bunker price and icebreaking fee reduction (with assumed navigation season length of 9 months) on the other. (Liu & Kronbak 2010).

Fig. 19. The assessed profitability of some examined route options from Liu & Kronbak (2010); profit per year as a function of bunker price and navigation season length (with a constant reduction of 85 % in icebreaking fees) on the left, and as a function of bunker price and icebreaking fee reduction rates (with assumed navigation season length of 9 months) on the right. Data source: Liu & Kronbak 2010.

4.4.4. Sea ice conditions and the increasing access

Also more detailed studies of the sea ice conditions and the changing marine access have been performed. For example, Stephenson et al. (2013) focus on providing realistic account of the implications that the changes in ice cover have for Arctic marine access. Their “approach combines projections of 21st-century Arctic technically accessible area, navigation season length, and temporal variability to simulate marine access as a function of both climatic (ice) conditions and vessel class” (Stephenson et al. 2013, 886).

The future sea-ice characteristics for the Stephenson et al. examination are from ice concentration and thickness simulations from the Los Alamos sea ice model (CICE) component of CCSM4, and relevant data is obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive. Projections are based on sea ice simulations for three RCP scenarios (4.5, 6.0, and 8.5) during the early
Stephenson et al. (2013) show that ship-accessible area and navigation season length increase in all scenarios, sharing broadly similar geographic patterns. Nevertheless, the RCP scenario remains significant. Especially the highest radiative forcing scenario (RCP8.5) provides notable increase of access for PC6 and OW vessel classes, also compared to RCP scenarios 4.5 and 6.0: by late century, over 90% of the reference area of the study (IMO Arctic Ship Guidelines Boundary) becomes accessible to open-water vessels from July to November, resulting in a period that is four months longer than under RCP6.0. In addition, PC6 vessels gain access to at least 80% of the reference region from February to June under RCP8.5, whereas the corresponding rate under RCP6.0 is less than 50%. Fig. 20 illustrates the accessible areas of Arctic under RCP6.0 by vessel type in summer and winter.

Under RCP8.5, the polar-classed vessels examined (PC3 and PC6) gain technical access to up to 96% (PC3) and 91% (PC6) of the reference region in summer by the middle of this century, rising to 98% and 98%, respectively, by late-century. Even for the RCP4.5, simulations estimate 93% and 82% summer access by mid-century, rising to 95% and 90% by late-century, respectively. However, there are strong regional contrasts, especially concerning the variability of navigation seasons and thus the reliability of the routes. All in all, the situation regarding even the most likely accessible trans-Arctic passage—the Northern Sea Route—will remain uncertain in the near term, and great variation from year to year will occur for all vessel classes. (Stephenson et al. 2013.)

Yet it must be recalled that the Stephenson et al. examination is based on a single-model simulation, and its results reflect only the scenario-based uncertainty between the RCPs (Stephenson et al. 2013). In addition, the ice extent is greater in the used model than the CMIP5 29-model mean through most of the 21st century, implying that the results may be rather conservative (Stephenson et al. 2013).
Despite this, the significance of regional differences and the overall variability of the navigation season are appropriately highlighted.

A similar study of the sea ice retreat and related increase in maritime access, though based on multi-model simulations, is performed by Khon et al. (2010). On the grounds of correspondence between hindcast simulations and satellite observations, they have selected five CMIP3 models for simulating the future ice conditions of the Northern Sea Route, and three models for Northwestern Passage simulations. Khon et al. emphasize that the selected models successfully reproduce both the seasonal cycle and the spatial sea ice distribution (for the present climate); that is, dimensions that both are crucial concerning the maritime accessibility and the length of navigation season.

Khon et al. utilize the A1B SRES scenario characterized by rapid economic growth, global population reaching up to nine billion in 2050, and balanced emphasis on all energy sources. According to the simulations, even moderate increases in concentrations of greenhouse gases and aerosols, consistent with scenario A1B, lead to significant changes in ice cover and thus the marine access.

At the end of the twenty-first century, models project a total increase in the NSR navigation length of about 4.5 (±1.3) and 3.6 (±1.7) months compared to current situation, averaged over the selected and all models, respectively. With regard to NWP, the changes are more moderate, with increases from 2 to 4 months. The projected development is rather steady and linear in the case of NSR, whereas the changes in access via NWP centre on the latter half of the century. Fig. 21 visualizes the development. (Khon et al. 2010.)

Khon et al. use a rather rough approximation of supposed linear dependence between the freight rate and total Arctic sea ice extent to estimate the future feasibility of trans-Arctic routes. Such analysis implies that the aggregate costs of freight transportation via Arctic will become competitive in large scale during the twenty-first century, resulting eventually in a saving of 15 % compared to the transit through the Suez Canal by the end of the century. (Khon et al. 2010.)

4.5. The Arctic challenges of shipping

Though the maritime conditions in the Arctic are undisputedly changing, certain characteristic features of the Arctic region will remain unaltered and thus continue affecting the Arctic marine activities. When assessing the most likely challenges of the future Arctic shipping, the share of natural conditions as well as technical and infrastructure-related issues needs to be considered. All in all, securing the safety and the well-being of both humans and the environment constitutes questions of notable concern especially
in the remote locations of the Arctic. These issues will be discussed here in detail, in order to comprise as realistic picture of Arctic shipping conditions as possible.

4.5.1. Sea ice

First and foremost, it is the sea ice that makes the maritime conditions in the Arctic so demanding and risky: “Without sea ice, the needs for environmental information in the Arctic would be little different from the world’s other oceans” (AMSA 2009, 160). The annual cycle of freezing and melting will remain as an essential part of Arctic waters, although the magnitude and thus the significance of the phenomenon may diminish. As mentioned before, the ice-free Arctic refers to the situation in which the total extent of Arctic sea ice cover is less than one million square kilometers. In such conditions, the coincidental occurrence of sea ice is very likely, and the demand for ice information is prominent. (AMSA 2009)

*Information about sea ice* is reasonably available at present, but as the number of vessels and voyages in the Arctic increases, the level of demand also rises. *The question is not so much about the quality and the contents as the quantity and the extent of the provided information*. The parameters are likely to remain the same, but they will be required over larger geographic areas and for longer periods of the year. “Operators will still need to know where the ice is and isn’t; where it’s going to be, how closely packed it is and how thick and strong it is; generally, how difficult it will be to go around or, when necessary, go through” (AMSA 2009, 160). The demand spans real-time data as well as short and long term projections, and both commercial and national services supply. (AMSA 2009.)

The occurrence of sea ice gives rise to certain demands and restrictions concerning the vessels operating in the Arctic. *IMO has taken special notice of the matter*, and it has published and afterwards updated a rather detailed report focusing on the *questions of safety and responsibility in the ice covered Arctic waters*. In Guidelines for ships operating in Polar waters IMO states that “only those ships with a Polar Class designation or a comparable alternative standard of ice-strengthening appropriate to the anticipated ice conditions should operate in polar ice-covered waters”, while ice-covered waters are defined as “polar waters where local ice conditions present a structural risk to a ship” (IMO 2010, 6 & 7).

*The system of Polar Classes* designates different levels of capability of ships operating in ice-covered waters (IMO 2010). In other words, *vessels that belong to a certain Polar Class are supposed to manage in specified ice conditions*. The general descriptions of the classes, and their correspondence to Finnish-Swedish Ice Class Rules are presented in Table 4. Furthermore, *IMO sets recommendations concerning the self-sufficiency and the standards of equipment for the Polar Classed vessels*. For example, ships with high classification (Polar Classes 1 to 5) “should have sufficiently available and reliable facilities to maintain a life sustaining environment in the event of an emergency and/or of extended ice entrapment” (IMO 2010, 14).

Also the structural vulnerability of classified ships is regulated, as “all Polar Class ships should be able to withstand flooding resulting from hull penetration due to ice impact” (IMO 2010, 13). In general, when navigating in the Arctic, *one should be prepared for the possibility of hazardous ice impact*.


<table>
<thead>
<tr>
<th>FSICR</th>
<th>First year ice thickness</th>
<th>Polar Class</th>
<th>General description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICE-1A</td>
<td>1.0 m</td>
<td>PC 1</td>
<td>Year-round operation in all Polar waters</td>
</tr>
<tr>
<td>ICE-1A</td>
<td>0.8 m</td>
<td>PC 2</td>
<td>Year-round operation in moderate multi-year ice conditions</td>
</tr>
<tr>
<td>ICE-1B</td>
<td>0.6 m</td>
<td>PC 3</td>
<td>Year-round operation in second-year ice which may include multi-year ice inclusions</td>
</tr>
<tr>
<td>ICE-1A</td>
<td>0.8 m</td>
<td>PC 4</td>
<td>Year-round operation in thick first-year ice which may include old ice inclusions</td>
</tr>
<tr>
<td>ICE-1B</td>
<td>0.6 m</td>
<td>PC 5</td>
<td>Year-round operation in medium first-year ice which may include old ice inclusions</td>
</tr>
<tr>
<td>ICE-1B</td>
<td>0.5 m</td>
<td>PC 6</td>
<td>Summermarine operation in medium first-year ice which may include old ice inclusions</td>
</tr>
<tr>
<td>ICE-1A</td>
<td>0.6 m</td>
<td>PC 7</td>
<td>Summermarine operation in thin first-year ice which may include old ice inclusions</td>
</tr>
<tr>
<td>ICE-1B</td>
<td>0.5 m</td>
<td>PC 1 to PC 6 may be assigned additional notation ICEBREAKER</td>
<td></td>
</tr>
</tbody>
</table>
Therefore no pollutants should be carried directly against the shell in hull (IMO 2010). That is, even though Polar Classed ships are designed for transiting through icy waters, the unpredictability of sea ice conditions should always be borne in mind. In addition, due to the extreme stress caused by ice encounters, special attention to structural degradation should be paid, and appropriate structural surveys should be regularly executed (IMO 2010).

The possibility of making the IMO guidelines mandatory has been discussed, but no conclusive agreement has yet been achieved. The binding instructions regulating both Arctic and Antarctic shipping are known as the IMO Polar Code, and the primary function of the code is to ensure the same level of safety for persons, the environment and the ships in Polar waters as in other waters. The remaining challenges in the development of Polar Code relate to geographical limitations, differing views on the additional risks resulting from operating in Polar waters, and finally the mitigation and management of these risks. Also some disagreements concerning the level of need for additional environmental protection measures have hindered the development and implementation of the code. (Østreng et al. 2013.)

Navigating in ice covered waters requires additional caution, and special instructions for Arctic operators have been compiled. The advisory of the American Bureau of Shipping (ABS 2014) focuses on the Northern Sea Route, but for the most part its contents apply to the Arctic waters as a whole, too. The key principle is that the power and the strength of ice should never be underestimated, as the forces involved are enormous which may cause the ice cover act in a rather unpredictable way. Ice may pose remarkable pressure against the hull of the vessel due to the drift of the ice floes, and ice drifting with a speed of more than 1.2 knots comprises notable danger to navigation.

The strength of ice pressure may even result in a situation in which icebreaker assisted transits become impossible, as the ice packs fill in the open trail behind the breaker almost immediately. In the worst case, icebreakers themselves get stuck and become helpless, and the escorted vessels are in a serious risk of getting crushed by ice. Some particular areas and geographical formations are likely to induce dangerous levels of ice pressure, and thus they should be avoided if possible. For example, straits and drift separation areas at the borders between fast ice and drifting ice are places where avoidable pressures may occur. (ABS 2014.)

Considering the choice of the best sailing route, a constant course decided beforehand cannot be maintained, but the master of the ship will have to work patiently with the ice, trying to find a path of least resistance through the ice mass. On the other hand, changing the course in icy waters is challenging, as it requires a much larger turning circle and greater power than in open water. Ice should be encountered with moderate speed and at an angle on 90 degrees in order to minimize possible structural damages. Also, it is essential to keep the vessel moving at all times, since a stationary vessel may easily become locked in the ice and thus lose all maneuvering capability, ending up being carried by the ice in the direction of the drift. Backing in ice should be considered as a last option—it should only be attempted when absolutely necessary. Moving backwards exposes the most vulnerable parts of the ship to the enormous force of ice, and damage from ice to the rudder and propeller may eventually lead to the immobilization of the ship. (ABS 2014.)

Currently most ships do require icebreaker assistance when transiting the Arctic waters, but the introduction of the so-called double-acting ships (DAS) may notably alter the situation in the near future. Double-acting ships have “double-acting operation design which allows the vessel to travel the traditional bow ahead in open water and, by using a propeller system that turns 180 degrees, to go stern ahead in ice-covered waters” (AMSA 2009). Double-acting ships usually manage by themselves in light and medium ice conditions—that is, in ice cover with up to 1.5 m thickness—but nevertheless need some traditional icebreaker assistance in particularly severe winter conditions (AMSA 2009).

With regard to the traditional icebreaker escort assistance, there are two principal methods that are applied according to the severity of conditions. In leading, the icebreaker creates a channel through the ice, and the escorted ships follow at predetermined distances and speed. In towing, the supported vessel is fastened to the icebreaker, in which case there is no gap between the vessels. Leading is a fairly easy and thus a primary option, used in light and medium ice conditions, whereas towing is a rather laborious measure, used mainly in heavy ice conditions. (ABS 2014.)
4.5.2. Weather and other natural conditions

In general, the Arctic is defined by extreme seasonal variability, as manifested by the cycle of freezing and melting of sea, the midnight sun in the summer and the polar night in the winter, and the temperatures varying from extreme cold to uncomfortable warmness (AMSA 2009). There is thus a multitude of aspects which affect the operational conditions in the Arctic—both alone and in interplay. In conjunction with the remoteness of the Arctic, such rather unique extremities give rise to a need of special and even tailor-made facilities and infrastructure.

Reliable maritime weather forecasts are of essential importance from the perspective any kind of marine activities. “Accurate forecasts of sea ice, wave height, wind direction and speed, visibility, temperature and superstructure icing are the most important routine forecast parameters for shipping,” and they are needed in the Arctic waters “with at least the same accuracy and timeliness requirements as on the other oceans” (AMSA 2009). Providing accurate and timely weather forecasts for the Arctic is in principle possible, as the forecasts “are based on the same tools using the same techniques as in other areas of the world,” but nevertheless “the scarcity of observations in the Arctic makes the monitoring of the weather more difficult than in areas with more observations” (AMSA 2009).

There are a few central meteorological phenomena affecting the Arctic shipping, related namely to cold temperatures (icing and freezing), low visibility (summer fogs and blowing snow), and rapidly developing unpredictable storms (polar lows).

Ship icing occurs when sea water, snow and/or floating ice accumulates on the above-the-water surfaces and structures, and then freezes. Such icing happens practically throughout the year, posing significant threat to safety if no measures are taken. Ice gathers especially in the forward parts of the vessel and above the vessel’s center of gravity, reducing the stability and affecting the trim of the vessel. The mass of the accrued ice may reach notable magnitude, as the thickness of ice cover can be as much as 1 m. (ABS 2014.)

Apart from icing due to external humidity, freezing may happen because of the mere low temperatures. Such freezing of hatch covers and water lines can paralyze even ice classified vessels, if they are not appropriately prepared for operations in extremely low temperatures. In addition, freezing may pose structural threats to the vessel, as the construction materials have to perform at temperatures close to their brittle transition temperature, where they lose their elasticity. Ballast tanks and fresh water tanks can freeze and become unusable. Also fuel and lube oil can cool too much, reaching the pour point and becoming too stiff to be used. Apart from the unusability, the freezing of internal tanks is potentially hazardous to the structure, as the volume of water-based liquids increases due to the phase change. (ABS 2014.)

Freezing temperatures naturally pose challenges to the crew of any ship and give rise to questions concerning the management of emergency situations. Due to very cold conditions, extra care of appropriate clothing and additional equipment must be taken. The necessary standard of equipment has to be borne in mind also when sizing the lifesaving appliances, as low temperature clothing is rather bulky. The operability of lifesaving appliances at the expected low temperatures must be secured by heating the propulsion system for the lifeboat and keeping the doors from freezing. (ABS 2014.)

Frequent and extensive fogs are common in the Arctic, especially during summer months. Sea fog occurs typically near the edge of concentrated ice, and it forms either when warm, moist air moves over colder seawater or cold air moves over warmer seawater. Also blowing snow may reduce visibility near zero, even without presently occurring snowfall. Very hazardous loss of perspective may occur when the sky and snow assume such uniform whiteness that the horizon becomes practically indistinguishable. Reduced visibility is of particular concern in the Arctic waters, as the presence of dangerous ice floes and icebergs is always more or less probable. (ABS 2014.)

Some meteorological phenomena are characteristic of relatively remote polar areas, and thus the underlying mechanisms are understood somewhat poorly. For example, polar lows are small but intense mesoscale vortices that have a rather short lifetime (Rasmussen & Turner 2003). They usually form either near the coast or near the edge of the ice sheet where cold air flows out onto relatively warmer open air, causing rapid increases in wind speed or snow flurries (ABS 2014). Despite their short lifetime polar lows can pose remarkable threat to Arctic activities, since in extreme cases they may involve winds of hurricane force and bring heavy snowfall to some areas (Rasmussen & Turner 2003). In addi-
tion, polar lows are rather unpredictable, and forecasting still presents many challenges (Rasmussen & Turner 2003).

4.5.3. Infrastructure and technical issues

The scope of infrastructure may be defined either broadly or in a more restricted way, depending on the aim of the examination. In the AMSA, infrastructure is understood very broadly “to address all major aspects of marine shipping, including vessels and crews, the systems needed to gather and supply accurate and timely information for safe navigation and operations, the personnel and resources needed to respond to a variety of potential emergencies, port reception facilities for ship-generated waste and the shoreside facilities needed to provide supplies and logistics in support of marine shipping and emergency response” (AMSA 2009, 157). Defined this way, the number of infrastructure-related questions is great, and many such questions have already been discussed in earlier sections. Hence the currently applied definition of infrastructure is narrower, and the focus is on the structural and technological framework in which all marine-related activities have to be performed.

With regard to mapping and hydrography, Arctic waters are not very well charted. This is mainly due to the inevitable limitations of historical survey methods, as the accuracy of charting has in part been based on the amount of marine traffic. The high costs and the volatility of conditions have kept the number of Arctic voyages very limited, resulting in partial and incomplete hydrographical data. Such

![Fig. 22. Search and rescue areas in the Arctic according to the 2011 agreement. Source: Arctic Portal Library 2014.](image)
low level of coverage and quality gives rise to an unfulfilled demand, especially as the amount of maritime activities is likely to increase notably. (AMSA 2009.)

Navigational aids as well as safety and navigation information broadcasts are necessary for the existence and development of safe and effective maritime activities. Arctic waters comprise an area which is not served by any single broadcasting system, but Arctic mariners have to rely on a patchwork of different systems. Nowadays, ships usually use combination of satellite positioning and traditional navigation techniques, and the communications provide services sufficient enough for the lower Arctic, whereas the high Arctic is in the fringe and occasionally out of reach. (AMSA 2009.)

The analogue radio facsimile broadcast is the historical standard for communicating weather, wave and ice information to the ships at sea, and despite the world-wide rise of digital communications its role as an important source of information in the Arctic is unquestionable. Even today, several radio stations around the Arctic broadcast analysis and forecast charts for sea ice, icebergs, sea state and weather, as well as provide vessel traffic services and general marine communications. Nevertheless, most modern ships are equipped with satellite digital communications equipment, relying on geostationary INMARSAT satellites. However, such satellites do not provide service northward of about 80 ° N latitude, whereas the IRIDIUM constellation of 66 polar orbiting satellites provides worldwide coverage, including the Arctic. The data transfer rates with IRIDIUM are however very low (less than 9.6 kb/s), decreasing the feasibility of communicating ice charts and satellite images to ships in the Arctic. (AMSA 2009.)

In addition to the above-mentioned requirements for vessels and their standard of equipment, the conditions in the Arctic waters demand very much from the crew. The professional skills of the mariners are tested in everyday situations, as the Arctic offers significant navigational challenges. However, the training of the skilful officers has mostly been on-the-job, with relatively little formal education. In future, the need for ice navigators increases, as well as the insistence on regulated qualification. For example, IMO’s guidelines recommend more formal training focusing on Arctic-related issues in conjunction with simulations of possible emergency situations. (AMSA 2009.)

The remoteness and challenging conditions of the Arctic waters gives rise to extra concern related to the search and rescue (SAR) and spill response capabilities. Furthermore, as the amount of Arctic marine activities increases, it is clear that the statistical probability of serious incidents also rises. The limited number of appropriate equipment and experienced personnel in conjunction with the sensitivity of the Arctic ecosystem underlines the importance of determined and rapid response. Processing and distributing the relevant information as fast as possible comprises the cornerstone of efficient incident management, especially in the remote locations of the Arctic. Thus the functional cooperation of different state authorities and commercial operators is of crucial importance. (AMSA 2009.)

There have been both bilateral and regional SAR agreements between Arctic States for providing the needed response in certain Arctic areas earlier, but no Arctic-wide agreement existed until 2011. The agreement was established with the contribution of the Arctic Council, and its main objective is to strengthen aeronautical and maritime search and rescue cooperation and coordination in the Arctic. According to the agreement, the Arctic is divided into specific search and rescue areas, and each of the Arctic Council member states has responsibility for its indicated area (see Fig. 22 for details). (Østreng et al. 2013.)

Nevertheless, the current SAR infrastructure in the Arctic is in general very limited and, in addition, regional variability is great. This results in some areas of Arctic waters being practically isolated with regard to incident response capabilities. Around the Arctic, there are fixed wing aircrafts and helicopters as well as icebreakers and seasonal patrol vessels utilizable for SAR, but long distances, weather and other operating conditions may inhibit their efficient usage. The insufficient shoreside infrastructure needed to provide basic logistics and support functions for SAR missions also hinders taking action. (AMSA 2009.)

In addition to the lack of SAR related shoreside infrastructure, the overall level of port services in the Arctic is rather low. There are few deepwater ports and places of refuge available, and facilities for ship-generated waste or towing services may be inadequate. Such shortages directly influence the level of risk associated with shipping in the Arctic, and thus affect the development of marine insurance rates. (AMSA 2009.)
All in all, places of refuge are essential for executing safe maritime activities, as they are the locations in which “a ship in need of assistance can take action to enable it to stabilize its condition and reduce the hazards to navigation, and to protect human life and the environment” (AMSA 2009, 179). Hence the vagueness concerning the Arctic shoreside infrastructure poses a major hindrance to the appropriate utilization of Arctic waters. The situation is particularly uncertain among the northern coast of Russia, where even more than half of the existing 50 ports on the Northern Sea Route are out of operation (Østreng et al. 2013). Apart from the several well-equipped deepwater ports along the NSR, there are notable obscurities in the statuses of existing ports at present, concerning especially the openness to foreign vessels as well as the availability and the quality of services (Østreng et al. 2013).

Spills of oil and other hazardous materials comprise a question of additional concern in the Arctic, since the long distances and the presence of sea ice significantly hinder executing appropriate measures on the one hand, and because the Arctic environment is especially vulnerable on the other. Additionally, the cold temperatures (that are very common in the Arctic) slow down the rate of biological degradation of oil, leading to increased durations and more extensive areas of exposure. Thus even an incident of moderate degree may in the Arctic conditions result easily in a vast ecological disaster. (Østreng et al. 2013.)

4.5.4. Icebreakers in the Arctic

Baltic Icebreaker Management defines icebreakers as follows: “An icebreaker is a ship that is intended to break ice in order to escort merchant vessels, to do ice management or to carry out some other special task in ice” (Riska 2011, 4). Similarly, according to IMO (2010, 7), “Icebreaker means any ship whose operational profile may include escort or ice management functions, whose powering and dimensions allow it to undertake aggressive operations in ice-covered waters”.

Though the main function of an icebreaker is undeniable breaking the ice, there are further requirements for a good icebreaker than the mere icebreaking performance. Stable and sufficient speed in the ice conditions of the intended operational area is a crucial factor, and the ability of providing appropriate services (escorting, tugging, possibly other support functions) is of determining importance. Also, the significance of competent crew to the overall performance must not be understated, as the potential of the most capable icebreaker cannot be utilized otherwise. (Riska 2011.)

Depending on the applied definition of icebreaker and the purpose of each account, the estimates concerning the number of icebreakers in the world lie somewhere between fifty and slightly over one hundred vessels (AMSA 2009, Riska 2011, Suomen Arktinen Seura 2013, USCG 2013a). For example, a study performed by the United States Coast Guard (USCG 2013a) charted the icebreakers with installed power of at least 10 000 horsepower; the results include altogether 78 vessels categorized by country, installed power and age. The outcomes of a listing by the Baltic Icebreaker Management are similar, as slightly more than 80 vessels are recognized as icebreakers (Riska 2011).

With regard to the world icebreaker fleet, the dominance of Russia is indubitable. Of the current 78 vessels categorized as icebreakers by USCG (2013a), altogether 37—that is, almost 50 %—fly the Russian flag. In addition, out of the ten most powerful icebreakers in the world, eight are owned by Russians (AMSA 2009). In general, the world’s icebreaker fleet is getting rather aged, and the pressure to modernization and renewals comprise an acute issue worldwide.

However, the status quo is not likely to alter remarkably—at least in the short term—as Russia invests heavily in fleet acquisition. According to the account of USCG (2013a), Russia has four icebreaking vessels under construction and further eight planned. Besides the high count of new icebreakers, the forthcoming vessels are of rather considerable scale, too. For example, the Balticysky Shipyard in St. Petersburg is already building a prototype vessel—the LK-60 “Arktika”—that will be the world’s most powerful icebreaker with the overall power of 60 MW (Barents Observer 2013c). The ship will be 173 meters long and 34 meters wide, and it is meant to be able to sail in up to 3-meter thick ice (Barents Observer 2014a).

The nuclear-powered prototype vessel is planned to be ready for service in December 2017, and the two next similar icebreakers should be ready for delivery in 2019 and 2020 (Barents Observer 2014a). Russia has thus determinedly ensured its capability to provide appropriate icebreaking services in the Northeastern Passage, which implies that Russia takes the commercial potential of trans-Arctic shipping
seriously enough. Furthermore, such signal is endorsed by the recent announcement concerning the operational usage of state-owned icebreaker company Rosatomflot’s fleet. Despite the constant cash flow from nuclear-powered tourist voyages to the North Pole, such Arctic tours will be history after summer 2015, as Rosatomflot focuses on serving the commercial shipping along the Northern Sea Route (Barents Observer 2014b).

Though Russia appears to have funds for such investments of remarkable scale, the politico-economic situation among the Arctic countries of Northern America, for example, seems to pose much more strict limitations on developing the fleet. In the United States, the Coast Guard’s active polar fleet includes currently only two vessels categorized as icebreakers (USCG 2013a), and future plans have thus far remained somewhat obscure. According to the USCG fact sheet, “the Coast Guard now is in the preliminary phase of a new polar icebreaker acquisition project [which] includes developing a formal mission need statement, a concept of operations, and an operational requirements document – all necessary before developing and implementing a detailed acquisition project plan” (USCG 2013b). Such a statement strongly implies that no new vessels with icebreaking capabilities will be commissioned in the near future.

The situation with regard to Canada’s Arctic preparedness is not substantially more promising. While the Canadian Coast Guard operates currently six icebreakers (USCG 2013a), the fleet is undeniably aging and thus demands continuous overhaul (CBC 2013). For example, the flagship of Canadian polar fleet—the Louis S. St. Laurent from 1969—was originally scheduled for decommissioning already in 2000 (The Globe and Mail 2014). However, due to constant delays in acquiring and delivering a substitutive vessel, the Louis S. St. Laurent is yet supposed to serve until late 2017—that is, until the completion of the John G. Diefenbaker, the new flagship of Canadian Coast Guard (The Globe and Mail 2014).

Nevertheless, the worldwide interest in developing operability in ice-covered waters is clearly distinguishable, as many countries with more or less close connections to polar regions have announced their forthcoming vessel acquisitions. For example, China and Norway are doubling their icebreaker fleet—from one to two vessels—within a few years (China Daily 2014, Barents Observer 2013a), and despite the withdrawal from the European polar research icebreaker project due to financial reasons (YLE 2011), Germany is planning to build a new polar vessel of its own (Alfred-Wegener-Institut 2014). In addition, the United Kingdom is purchasing a new polar research flagship with greater ice-strengthened capability and longer endurance compared to the existing British fleet (British Antarctic Survey 2014). All in all, recent progression seems to result in a situation, in which the role of certain traditionally powerful Arctic actors has eventually been questioned, as more and more vessels with polar icebreaking capability become available to both research and commercial use.

In any case, the icebreaking technology is developing, and the significance of traditional single-acting icebreakers is perhaps diminishing along the introduction of more flexible multi-purpose vessels. As mentioned earlier, the so-called double-acting ships (DAS) may alter the icebreaking scene notably. Double-acting-ships are relatively independent in light and medium ice conditions, while the payload of such ships is yet of notable magnitude (AMSA 2009). According to the manufacturer, the prototype DAS vessel—MS Norilskiy Nickel— has successfully demonstrated its performance and logistics efficiency, exceeding all contractual performance requirements (Aker Arctic 2006).

Also the repertoire of functions that more traditional icebreakers are supposed to perform has become rather wide, as they are meant to serve as multifaceted offshore platforms, providing various essential services to other vessels. In addition to the more obvious services such as maintenance of shipping tracks and escorting ships, icebreakers have to participate in search and rescue as well as marine security missions, function as a base for scientific enquiries, re-supply local communities, and represent the flag country (AMSA 2009).

Furthermore, the development of arctic oil and gas extraction poses new challenges to icebreakers and other supply ships. The possibility of appropriate operations in case of incident (e.g. spill of oil or other hazardous material) must be ensured in order to maintain the desired level of responsibility. However, the icy conditions in the Arctic hinder the incident prevention and response remarkably, resulting thus in a need of novel and innovative solutions.

With regard to the Arctic climate change and the related decrease of sea ice, less ice does not automatically mean more favorable marine conditions or reduced need for icebreaking services. Vice versa,
the disappearance of relatively light first year ice may eventually result in increased drifting of thick multi-year ice, posing thus more substantial hazard to vessels with minor or no ice-strengthening. Furthermore, especially in places of narrow passage—such as straits and fragmentary archipelago—floating multi-year ice may pack, forming practically impenetrable obstacles for vessels without notable ice-breaking capability. Hence, though the absolute extent and volume of sea ice in the Arctic region is likely to decrease in future, a considerate demand for icebreakers in the Arctic will surely remain. (Østreng et al. 2013.)
5. The emissions from shipping in the Arctic today and tomorrow

In this section, the magnitude and significance of emissions from maritime activities are examined. Special attention is paid to the emissions originating in and/or having notable effects in the Arctic region. The examination is divided into three subsections: the first subsection deals with the long-lived greenhouse gases (mainly carbon dioxide CO₂), the second addresses the most important air pollutants (nitrogen oxides NOₓ, sulfur dioxide SO₂ and particulate matter PM), and the third one focuses solely on black carbon (BC) and its special relevance concerning the Arctic.

All of the discussed emissions are produced during the combustion processes in ship engines, indicating that they result mostly from the usage of fossil fuels—such as relatively impure heavy fuel oil (HFO) or distilled marine gas oil (MGO). However, the exact origin of these emissions varies; most of the emissions form as the components of fuel get oxidized, but some emissions have a basis in the combustion air.

For example, as fossil fuels are combusted, the carbon stored in them is almost entirely emitted as CO₂. Furthermore, the CO₂ emissions from marine engines are a function of the carbon content of the fuel rather than the engine or combustion technology. Similarly, SO₂ emissions have origin in the fuel, and they are primarily a function of the sulfur content of the fuel. Contrary to this, the level of NOₓ (including both NO and NO₂) emissions is par excellence connected to the air-fuel mix and combustion temperatures, since NOₓ emissions are generated as the nitrogen from the combustion air is oxidized. Hence both fuel and engine types—which eventually determine the combustion conditions—have notable influence on NOₓ emissions. (IPCC 2002.)

![Emissions from global shipping](image_url)

**Fig. 23.** Total emissions from global shipping by emission species in 2007 and in 2050, according to IMO’s second greenhouse gas study. With regard to 2050, the column represents projected average value, whereas the error bars refer to minimum and maximum values from a set of scenarios. The used values are picked or calculated from the baseline case values of each scenario. Data source: Buhaug et al. 2009.
PM emissions, in turn, are a compound of residual components of combustion processes. International Maritime Organization (Buhaug et al. 2009) describes particulate matter as follows:

*Particulate matter (PM) is a mix of non-volatile and semi-volatile compounds that do not fully participate in combustion or that are produced during combustion processes at high temperatures and pressures.*

Thus the mechanisms affecting the generation of PM emissions are manifold. In general, both the fuel quality and the combustion conditions have an influence. BC, for its part, is a subspecies of PM that is generated during incomplete combustion—that is, when there is not enough oxygen to yield a complete conversion of the hydrocarbon-based fuel into CO\(_2\) and water (AMAP 2011a). These issues will be discussed in detail in the following sections.

5.1. Greenhouse gas emissions

This section covers greenhouse gases from shipping. In general, exhaust gases are the primary source of emissions from ships, and CO\(_2\) is clearly the most important greenhouse gas emitted by ships, both in terms of quantity and of global warming potential (Buhaug et al. 2009). Thus the focus of this section is on CO\(_2\), whereas the data concerning other greenhouse gases such as methane (CH\(_4\)) and nitrous oxide (N\(_2\)O) can be found in the Fig. 23 and Table 5, which in part sum up the extensive assessment of emissions from global shipping set out in IMO’s second greenhouse gas study. At first, emissions from global shipping are assessed, after which an Arctic-specific scrutiny is provided. All in all, it is good to note that since CO\(_2\) emissions are long-lived, the location of emissions is not relevant from the climate effect perspective, and merely the total amount of emissions counts.

### 5.1.1. Global emissions

According to IMO’s study (Buhaug et al. 2009), global shipping caused 3.3% of all anthropogenic CO\(_2\) emissions in 2007, corresponding to an amount of 1050 million tonnes. The share of international shipping was approximately 870 million tonnes, which comprises 87% of the total shipping-based emissions. On the grounds of an exhaustive analysis concerning the development of global maritime activities (described more precisely in section 4.4.2), IMO has also assessed the future levels of emissions originating in shipping. Depending on the underly-

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<th>Table 5. Estimates for past and future emission levels (million tonnes), according to IMO’s second greenhouse gas study. The study involves various scenarios, which are utilized in evaluating projected values. The projected MAX, MIN and AVE values refer to maximum, minimum and average values of scenarios, picked or calculated from the baseline case values of each scenario. Data source: Buhaug et al. 2009.</th>
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<td>N(_2)O</td>
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<td><strong>Fig. 24.</strong> The projected development of CO(_2) emissions from international shipping. Source: Buhaug et al. 2009.</td>
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</table>
In this scenario, the total volume of shipping-based CO₂ emissions is estimated to be 2450—3640 million tonnes in 2050. This amounts to an increase of 133—247% from the 2007 level, and thus the overall trend of growth is very clear (see Fig. 24).

With regard to the climate impacts of these emissions, IMO (Buhaug et al. 2009) has evaluated radiative forcings based on the CO₂ from shipping for current and future emission levels. For the 2007 emissions, the relevant RF was calculated to be 49 mW m⁻², contributing approximately 2.8% of total RF from anthropogenic CO₂ in 2005. For the approximated 2050 emissions, RFs with magnitudes of 99—122 mW m⁻² are expected. Fig. 25 illustrates the history and the projected development of RF from CO₂.

5.1.2. Arctic emissions

Estimates of shipping-based emissions specifically in the Arctic region have also been presented, though with notable differences involved. For example, Corbett et al. (2010) have assessed that the CO₂ emissions in the Arctic were approximately 11.2 million tonnes in 2004, whereas the corresponding rate of Peters et al. (2011) is 20.3 million tonnes. Such differences are likely to result from varying definitions of the Arctic as well as inconsistencies among the methods used in gathering and processing the relevant data. In any case, the magnitude of estimates is similar, implying that the CO₂ emissions from Arctic shipping represent at most a few percent of global CO₂ emissions originating in maritime activities.

Based on the feasibility assessments and related transportation scenarios introduced earlier (in section 4.4), also projections of CO₂ emission originating particularly in Arctic shipping have been evaluated. However, it must be emphasized that the degree of uncertainty among such Arctic-specific projections is rather great, since they involve assumptions concerning both the future of global maritime in-
industry and the development of Arctic shipping conditions. There are numerous sources of inaccuracy in such projections, and an occurrence of unexpected turn may vitiate the projection as a whole.

Depending on scenario (Business As Usual / High Growth), Corbett et al. (2010) assume an annual 2.1 / 3.3 % growth in global shipping, of which a share of 1.8 / 5 % diverts through the Arctic in 2050, as well as a steady increase in in-Arctic shipping according to growth rates presented in Table 2. The two scenarios—BAU and HiG—thus result in CO₂ emissions of 45.7 and 153 million tonnes in 2050, respectively. It must be noted that the CO₂ emissions from fishing (e.g. 3.2 million tonnes in 2004) is excluded from these numbers. If the share of fishing is subtracted also from 2004 emissions, the projections imply remarkable increases of 308 and 1270 %, respectively, compared to the 2004 level.

Based on a more technical feasibility analysis, DNV (2010) has assessed possible CO₂ emissions from economically reasonable trans-Arctic traffic. Their estimate is 5.6 million tonnes of CO₂ emissions in 2050, which is notably less than the rates of the Corbett et al. (2010) study—even when compared merely to the share of in-Arctic container traffic (12 and 26 million tonnes in BAU and HiG scenarios, respectively).

An associated study (Peters et al. 2011), presumably relying on DNV’s technical shipping model, examines also the oil and gas extraction-related and other, non-transit shipping emissions. However, the emissions from shipping activities related to tourism, fishing and local re-supply are not included. The approximated rates for CO₂ emissions from oil and gas extraction-related shipping and other shipping are 10.7 and 20.3 million tonnes in 2050, respectively. In conclusion, these numbers total 36.6 million tonnes, which lies roughly in the middle of the estimates based on the different scenarios of Corbett et al. The Peters et al. study thus implies an increase of altogether 80 % compared to 2004 level.

5.2. Air pollutant emissions

This section discusses the most important air pollutants—that is, nitrogen oxides (NOₓ), sulfur dioxide (SO₂) and particulate matter (PM)—from marine activities. The scope of the examination is not arbitrary, as the emission species in question are of particular significance from the health and environmental perspective on one hand, and the role of global marine industry in producing such emissions is considerable on the other.\(^5\)

Shipping-based sulfur is emitted mainly as gaseous SO₂, which is oxidized in the atmosphere to sulfate (SO₄\(^{2-}\)). Sulfate in turn forms particles that affect the radiative budget both directly and indirectly. Sulfate particles scatter solar radiation by themselves and thus reduce the direct heating of the surface on one hand, and alter the cloud-related scattering on the other. Sulfate particles form cloud condensation nuclei, increasing droplet number densities and changing the reflectance and lifetimes of clouds. These mechanisms lead to a considerable negative forcing and consequent cooling of atmosphere in global scale. (Fuglestvedt et al. 2009.)

However, SO₂ emissions have remarkable detrimental effects on human health (by contributing to PM concentrations), on terrestrial and freshwater ecosystems (by acidification), on man-made materials and cultural heritage (by corrosion), and on biodiversity and forestry (UNEP 2012). The significance of such negative impacts due to SO₂ emissions from shipping is boosted by the fact that almost 70% of ship emissions occur within 400 km of coastlines, leading thus easily to reduced air quality in rather densely populated coastal areas and harbor settlements (Fuglestvedt et al. 2009).

In addition, the significance of negative forcing from sulfate must not be overstated, as sulfur-based emissions are rather short-lived. The short-term cooling impacts of SO₂ emissions and the related increase in sulfur concentration are eventually outweighed by the influence of CO₂ over the course of decades, while the effects of SO₂ emission reductions on health, acidification and eutrophication are unquestionably beneficial (Fuglestvedt et al. 2009).

\(^5\) Also the United Nations Environment Programme (UNEP) has recognized the role of global shipping with regard to SO₂, NOₓ and black carbon emission. For example, in its fifth Global Environment Outlook (GEO-5) assessment report UNEP (2012, 41) states that “The boom in global trade has led to significant emissions of CO₂ and key pollutants including SO₂, NOₓ and black carbon from international shipping”. 

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The significance of NOx emissions is above all based on their role as precursors of tropospheric and surface ozone \((O_3)\). Tropospheric ozone is located in the lower atmosphere, from 0–10 up to 20 km above the Earth’s surface, and is practically responsible for ozone’s impact on radiative budget and consequent warming of climate. Surface ozone in turn refers to concentrations of ozone at ground level, affecting both human health and the welfare of ecosystems. (UNEP 2012.)

Ozone is not directly emitted into the atmosphere but is formed when precursor pollutants—such as nitrogen oxides—react photochemically in the presence of sunlight. Due to the nature of ozone generation process, ozone-related effects are likely to manifest at some distance from the actual precursor emission sources. The importance of precursor pollutant emissions to ozone concentrations is notable, as photochemical reactions account for approximately 90 % of the ozone in the troposphere. Furthermore, around 30 % of tropospheric ozone eventually results from anthropogenic emissions. (UNEP 2012.)

Particulate matter, in turn, is the most important air pollutant causing damage to human health. Especially the PM with smallest particle sizes—particles of 2.5 \(\mu\)m in diameter or less—is of considerable hazard. For example, based on exposures to PM in 2004, the World Health Organization (WHO) has estimated that the premature deaths of 3.1 million people—approximately 5.3 % of premature deaths worldwide—are attributable to air pollution. In addition, studies indicate that there is no safe threshold for exposure, as even very low levels cause notable health damage. (UNEP 2012.)

The section is divided into three subsections. Air pollutant emissions from global shipping are examined in the first subsection, in which also the most important IMO’s regulations aiming at emission reductions are introduced. In the second subsection, estimates of emissions from Arctic marine activities are presented. The third subsection covers the projected climatic impacts—such as concentration changes and consequent alterations to radiative budget—resulting from the estimated emissions, utilizing spatial analysis to illustrate the geographical distribution of presumed effects.

5.2.1. Global emissions

According to IMO’s study, NOx emissions from global shipping were 25 million tonnes in 2007. Though the levels of NOx emissions from marine engines have already been constrained by regulation 13 of MARPOL Annex VI since the beginning of 2000, the absolute emission volume from global shipping is estimated to have increased from 19 million tonnes in 2000 to 25 million tonnes in 2007—that
is, 32 % altogether. Despite this, the introduction of regulation 13 has resulted in a reduction of about 6% of NOx emissions from shipping in 2007 compared to a no-regulation scenario, and the reduction in emissions for regulated engines, as compared to pre-regulation engines, is about 12–14% per tonne of fuel consumed. (Buhaug et al. 2009.)

The MARPOL Annex VI regulation 13 includes four different NOx emission categories—Tier 0, Tier I, Tier II and Tier III—which define the upper limits of NOx emissions. Tier 0 refers to the unconstrained situation, previous to the implementation of Tier I in the beginning of 2000. Tier II came into effect in the beginning of 2011, whereas the scheduling of Tier III is yet open to revisions. In addition, the implementation of Tier III applies only to certain Emission Control Areas (ECAs), which are presented in Fig. 26. The details of the emission categories are presented in Table 6. In spite of the planned measures, the NOx emissions from global shipping are estimated to be 33.3—51.0 million tonnes in 2050, resulting in an increase of 33—104% compared to 2007 level. (Buhaug et al. 2009.)

The amount of SOx emissions from global shipping was 15 million tonnes in 2007. However, due to strict policies limiting the heavy fuel oil (HFO) sulfur content—stated in regulation 14 of MARPOL Annex VI—the SOx emissions in 2050 are in fact projected to be lower compared to the 2007 level. The regulation 14 sets out limits for fuel sulfur content according to the two geographical subcategories, namely specific Emission Control Areas (ECAs, see Fig. 26) and non-ECAs (the rest of the world), and the limitations are meant to come into effect gradually, as Fig. 27 illustrates. A planned cap of 0.5% fuel sulfur content for non-ECAs, intended to apply from the beginning of 2020, may yet be postponed to 2025, depending on the results of a review completed by 2018. (Buhaug et al. 2009.)

The effects of regulation 14 have already been assessed; IMO has evaluated reductions in SOx emissions for 2008, since this is the first year in which both of the ECAs (the Baltic Sea since 19th of May 2006 and the North Sea since 22nd November 2007) have been fully in force. According to the

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<th>Tier</th>
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<th>NOx limit (g/kW-h)</th>
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<td>Tier I</td>
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<td>Tier II</td>
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<tr>
<td>Tier III</td>
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* Tier III applies only in emission control areas. "n" refers to rated engine speed (rpm).

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Table 6. The details of the MARPOL Annex VI regulation 13, limiting the levels of NOx emissions from shipping. Source: Buhaug et al. 2009.

Fig. 27. The planned reductions in fuel sulfur content, according to MARPOL Annex VI regulation 14. ECA stands for Emission Control Area. The reduction from 3.5 % to 0.5 % in non-ECA regions may be postponed to 2025 (dashed line), depending on the results of a review completed by 2018. Data source: Buhaug et al. 2009.
analysis, the SO\textsubscript{2} emissions from shipping in the ECA areas with limited 1.5 % fuel sulfur content are about 42 % lower compared to the hypothetical unregulated scenario—that is, with 2.7 % fuel sulfur content. Based on these outcomes, IMO’s estimates for SO\textsubscript{2} emissions from global shipping are 5.7—8.8 million tonnes in 2050, thus implying a decrease of 41—62 % from the 2007 level. (Buhaug et al. 2009.)

The composition of PM emissions from ship engines is a rather complex issue with various factors contributing. At least fuel quality, engine type and maintenance (combustion conditions), and vessel activity (accelerations and active decelerations) have significant influence on the properties and variability of PM emissions (Lack et al. 2009).

For example, fuel sulfur content is a crucial factor, and despite a certain constant residual of PM emissions in the case of completely sulfur free fuel, the emission factor (EF)\textsuperscript{6} of the total PM emissions is assumed to be linearly dependent on the fuel sulfur content (Jalkanen et al. 2012). In general, observations imply that high-sulfur fuels (>0.5% sulfur) emit more than twice as much PM as low-sulfur fuels (<0.5% sulfur) (Lack et al. 2009). The effects of fuel sulfur content to the composition and amount of PM emissions are illustrated in Fig. 28.

The engine type also counts, as combustion temperatures and pressures notably affect the properties of emissions. Large slow-speed diesel (SSD) engines run at higher temperatures and pressures than medium-speed diesel (MSD) engines, which gives rise to an increased number and total mass of produced particles in the case of SSD engines. On the other hand, long-haul ships with SSD engines generally burn low-quality residual fuels that often contain impurities (high amounts of sulfur and heavy metals), whereas smaller vessels with MSD engines use mostly distillate fuels such as marine gas oil (MGO). Though fuel impurities directly influence the composition of the produced PM emissions, the role of mere combustion conditions is needs to be taken into account. (Lack et al. 2009.)

Vessel activity affects engine load levels to some extent—and thus the composition of PM emissions—but the dependence is not straightforward. If the engine is run outside its normal operating load range, fuel consumption and emissions are likely to increase. Also running the engines on exceptionally low load levels (due to decreased speed) may result in undesirable effects, like in the cases of port maneuvers, slow steaming and ships that are breaking ice cover. However, with multi-engine installations it is possible to balance the load in a way that leads to optimal performance of the engines, producing thus minimal emissions. (Jalkanen et al. 2012.)

The IMO study (Buhaug et al. 2009) examines total PM emissions from global shipping, but no further analysis of the most important subspecies—such as BC—is yet provided. According to IMO’s estimates, global shipping produced altogether 1.8 million tonnes of particulate matter emissions in 2007. Mainly due to restrictions on fuel sulfur content and the remarkable effect fuel quality has on PM emis-

\[ \text{emission factor} = \frac{\text{emissions}}{\text{fuel consumption}} \]

\[ \text{Proportion of PM emissions} \]

\[ \text{Fig. 28. The composition of particulate matter (PM) emissions as a function of fuel sulfur content. Data source: Buhaug et al. 2009.} \]

\[ \text{A conversion value that is used to calculate emissions based on consumed fuel, usually expressed in g kWh}^{-1} \text{ or g t}^{-1}. \]

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sions, the level of PM emissions is projected to decrease to 1.1—1.7 million tonnes in 2050, which is about 5.6—39 % lower than in 2007.

5.2.2. Arctic emissions

Based on the Arctic-specific projections discussed earlier (Corbett et al. 2010 and Peters et al. 2011), estimates of present and future air pollutant emissions from Arctic shipping are also available. These rates are of particular interest considering the development of Arctic climate, since the geographical location of certain air pollutant emission species may have notable significance. For example, black carbon—a subspecies of PM—has been identified as a potential pollutant warming especially the Arctic climate.

The projections of future air pollutant emissions involve more variables than those focusing merely on CO₂, mainly due to the open questions concerning related technology and possibilities for emission abatements. For example, the EFs of CO₂ were constant in both studies, but this is not the case with air pollutants. Corbett et al. feature notable reductions in EFs of all major air pollutants, and Peters et al. presume reductions as well, but of a slightly lesser degree.

According to Corbett et al. (2010), NOₓ emissions from Arctic shipping are 196 thousand tonnes in 2004, increasing to 809 / 2652 thousand tonnes (an increase of 313 / 1253 %) in 2050 (BAU / HiG scenarios). The corresponding rates for SO₂ are 136 and 144 / 477 thousand tonnes (6 / 251 %), respectively, and, for PM, 13 and 19.2 / 65 thousand tonnes (48 / 400 %). The applied and apparently rather high rates of growth in Arctic shipping are clearly distinguishable, whereas the reasonability of these underlying presuppositions might be challenged.

Peters et al. (2011) estimate NOₓ emissions from Arctic shipping to be 491 thousand tonnes in 2004, increasing to 866 thousand tonnes (a change of +76 %) in 2050. For SO₂ and PM, the corresponding rates are 281 and 48.4 thousand tonnes in 2004, evolving into 112.2 and 60.7 thousand tonnes (−60 and +25 %) in 2050, respectively. Due to the varying assumptions underlying the projections, the outcomes of the two studies may not be directly comparable as absolute numbers. Despite this, the magnitude of estimates is similar, indicating a probable development of increasing Arctic emissions. (See also Fig. 37 for an illustrated compilation of relevant numbers.)

5.2.3. Further analysis

Based on the two above-discussed studies, also a number of more detailed and profound analyses have been executed, focusing mainly on the geographical distribution of the air pollutant emissions, the consequent changes in atmospheric composition, and the related impacts on radiative budget. Two inquiries stemming from the Corbett et al. study will be introduced here, as well as one utilizing the dataset of Peters et al.

A study performed by Ødemark et al. (2012) focuses on present-day (2004) concentration changes
and radiative forcing from shipping (and petroleum activities) in the Arctic region. The simulations are based on the inventories in Peters et al. (2011), utilizing chemistry-transport and radiative transfer models in order to produce relevant geographical distributions.

The outcomes of the Ødemark et al. (2012) study show that the concentration changes from current Arctic shipping centre on lower latitudes—mainly the Norwegian coast—whereas the impacts on RF budget apply to a larger area, including the High Arctic. For example, the NOx increase in the lowest 1.5 km is greatest in the vicinity of largest ports and busiest shipping lines; in these areas concentration changes up to 0.6 ppb occur. The geographical location of surface ozone (O3) concentration changes follows closely, as Fig. 29 illustrates. The greatest increases in ozone concentration are up to 3 ppb in summertime—that is, when the photochemistry is most active due to maximum insolation.

However, with regard to the tropospheric ozone column, the impacts spread to a more extensive area. Such development strongly implies that also the RF from increased ozone concentrations is distributed more widely than the actual emissions. As the results of the simulation show (see Fig. 29), the RF from changes in ozone concentrations eventually focuses on the High Arctic—that is, on an area rather remote from the prime source of NOx emissions. All in all, the annual RF caused by ozone originating in Arctic shipping is estimated to be 4.2 mW m⁻². (Ødemark et al. 2012.)

The SOx emissions from shipping also centre on lower latitudes and especially around the Norwegian coast. The sulfur-related emissions are among the most important RF contributors from shipping, as they cause both direct and indirect negative forcing. Estimates for in-Arctic totals of SOx-based direct and indirect RFs are -5.8 and -19 mW m⁻², respectively. (Ødemark et al. 2012.)

Dalsøren et al. (2013) examine the impacts of increased shipping on surface concentrations and radiative forcing on the grounds of Corbett et al. (2010) scenarios. They simulate the effects of the lowest and highest estimates of Corbett et al.—that is, the relevant emission estimates from Business As Usual (BAU) and High Growth (HiG) scenarios—in atmospheric models, and compare the outcomes in order to conceive the range of relevant possibilities in 2030.
The outcomes of Dalsøren et al. (2013) point out, for example, that the highest NO\textsubscript{x} concentrations are close to or within the presumed shipping lanes, and that the increases may regionally be above 200% in summertime compared to 2004 level. Such increases are likely to occur in the vicinity of the possible diversion routes—that is, in pristine regions, where marine activities are currently very sparse. In the same regions, the concentration of sulfate (SO\textsubscript{4}\textsuperscript{2-}) may increase up to 50% from 2004 due to SO\textsubscript{2} emissions from trans-Arctic traffic. The global changes in NO\textsubscript{x} and sulfate concentrations from 2004 to 2030 in different scenarios in summertime are presented in Fig. 30, in which also the significance of increasing diversion clearly illustrated.

The increasing concentrations have effects on the radiation budget, either directly or indirectly. The high levels of NO\textsubscript{x} contribute to the formation of ozone, which in turn leads to positive forcing. However, the O\textsubscript{3} generation from shipping is limited in the Arctic, as the highest concentrations occur outside the months with maximum insolation. Hence the observed seasonality of emissions has great importance, as well as their geographical location. The increases of sulfate concentration in the Arctic lead to negative forcing due to the scattering effects, whereas the considerable global-scale regulation-based reductions of SO\textsubscript{2} emissions cause positive RF of a rather significant magnitude. (Dalsøren et al. 2013.)

At first it might appear unintuitive that the scenario with maximum feasible reductions—the Business As Usual scenario from Corbett et al. (2010)—actually leads to largest global positive RF, but such development originates in the role of SO\textsubscript{2} emissions and corresponding effects on sulfate concentration. A scenario with the greatest abatements on one hand and smallest overall growth in marine activities on the other produces the least SO\textsubscript{2} emissions altogether, and thus leads to smallest possible scattering-based cooling effect (Dalsøren et al. 2013). Yet it must be remembered that the cooling impacts of SO\textsubscript{2} emissions and the related increase in sulfur concentration are short-term, and thus outweighed by the influence of CO\textsubscript{2} over the course of decades (Fuglestvedt et al. 2009).

Another study, by Winther et al. (2014), combines the Corbett et al. (2010) traffic scenarios and satellite based AIS data in order to gain geospatial ship type specific emission projections for the Arctic. The analysis takes both the predicted improvements in vessel energy efficiency (Energy Efficiency De-
sign Index, EEDI; see section 5.3.5 for more details) and regulation-based emission reductions by ship type into account, extending thus the scope of Corbett et al. (2010) notably and producing a rather precise and elaborate description of the possible development of shipping-based emissions and related spatial distributions in the Arctic. However, the effect of multi-engine installations on the engine load levels, and thus on the composition of emissions as well as the fuel consumption (see Jalkanen et al. 2012 for details), is not included in the model, giving rise to some inaccuracy—particularly with regard to PM emissions.

Winther et al. (2014) use the Corbett et al. BAU traffic scenario as a basis for their emission projection (with EEDI reductions and vessel type specific emission factors), focusing on the significance of possible Arctic diversion. They model the increases in relevant concentrations and the geographical distribution of the emissions. From 2012 to 2050, the NOx and SO2 emissions from Arctic shipping without diversion are estimated to decrease 32 and 63 %, respectively. The role of ship traffic on Arctic diversion routes in 2050 is nevertheless rather notable, as it is presumed to increase the total levels NOx and SO2 emissions 150 and 155 %, respectively. Thus, with the effect of diversion included, the total NOx emissions from Arctic shipping are calculated to increase 68 % (from 308 to 517 thousand tonnes), and the SO2 emissions to decrease 4.5 % (from 88 to 84 thousand tonnes).

The role of the diversion routes is clear also when examining the impacts of shipping-based emissions on the relevant surface concentrations in summertime in 2050. The increases in Arctic-wide average concentrations due to diversion traffic (percent of background) remain moderate—4.0 and 4.7 % for SO2 and O3, respectively—whereas the contribution of diversion emissions to regional concentrations may become very significant, soaring to above 1000 % for SO2 along the Arctic diversion routes, and to above 10 % for O3 in the High Arctic. Fig. 31 illustrates the projected changes in concentrations of SO2 and O3 from 2012 to summer 2050 due to emissions from total Arctic shipping. (Winther et al. 2014.)

5.3. Black carbon and its special relevance concerning the Arctic

This section focuses on black carbon emissions and the related general climatic mechanisms and impacts. Also more technical issues are examined, as the problematics of defining and measuring black carbon are discussed and the generation of BC emissions is explicated. On these grounds, some promising possibilities for gaining emission abatements are introduced, and their feasibility and cost effectiveness is assessed. In the end of the section, numerical and spatial estimates of present and future BC emissions are presented, and the presumed climatic impacts from these emissions are evaluated. The section concludes with a few critical notes concerning the role of the BC emissions originating in Arctic shipping, as the outcomes of certain studies appear to indicate that the overall magnitude of emissions from maritime activities in the Arctic region is eventually rather small.

5.3.1. General climatic mechanisms

Black carbon (BC) is subspecies of particulate matter emissions that due to its characteristics has notable significance for the radiative budget of the Arctic region, and thus the Arctic climate as a whole. BC is considered a short-lived climate forcer (SLCF), since it has a lifetime of days to weeks. The rather short lifetime of BC emissions eventually prevents their full interhemispheric mixing, giving rise to the additional significance of the location of the emissions. (Ödemark et al. 2012.)

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7 The health and environmental issues related to black carbon emissions are not assessed separately from those originating in general PM emissions (see section 5.2).

8 In general, SLCFs are components of emissions that have a relatively short lifetime in the atmosphere—days to about a decade—compared to main greenhouse gas CO2 (UNEP/WMO 2011). In some forums (see, for example, IGSD 2013), SLCFs are known as Short-Lived Climate Pollutants (SLCPs), emphasizing the related negative effects on human health and environmental welfare.
Black carbon causes radiative forcing via three separate mechanisms. First one is the direct aerosol forcing, which occurs through absorption of solar radiation in the atmosphere. This mechanism warms both the air at higher altitudes (that is, where the aerosols are located) and the surface, leading thus to positive RF. (AMAP 2011a.)

Second mechanism comprises of the aerosol-cloud interactions BC can participate. By decreasing cloud droplet size, BC can increase cloud optical thickness and cloud lifetime. Both these changes cause increases in the amount of solar energy reflected and hence cooling of the surface, which means negative RF. On the other hand, reinforcing the cloud cover makes it actually more efficient at trapping and re-emitting radiation from the surface, which in turn leads to warming at the surface. Altogether, the net influence of these aerosol effects in the Arctic is presumed to be cooling during summer and warming during winter. (AMAP 2011a.)

Third mechanism relates to the possibility of BC to deposit to snow and ice cover, reducing the surface albedo substantially. The remarkable significance of this last option is based on the fact that even part-per-billion concentrations of BC can have a notable influence. According to the AMAP (2011a, 48) there are two main reasons for this: “first, the absorptivity (mass absorption cross-section) of BC is about five orders of magnitude greater than ice in the visible part of the spectrum; second, multiple scattering in surface snow greatly increases the path-length of photons and the probability that they encounter non-ice particles.” Such mechanism leads to more effective absorption of solar heat, and hereby to surface warming and finally to positive RF.

5.3.2. Black carbon in the Arctic

Due to the manifold forcing mechanisms and the relatively short lifetime, BC emissions of same magnitude but from differing latitudes can in fact lead to notably dissimilar total consequences. This is why BC emissions originating in the Arctic have much more relevance compared to the emissions from lower latitudes. Changes in RF per unit of BC emission have a strong dependence on the latitude of the source, as Fig. 32 illustrates.

When assessing the significance of BC emissions, not only their spatial distribution, but also their timing may have remarkable bearing. This is due to two reasons: the temporal variations in the total extent of snow and ice cover, and the temporal variation in the intensity of solar radiation. Yet there seems to be a certain inconsistency in the impact of season: on the one hand, the snow and ice cover is largest in winter; on the other hand, the Arctic receives the most sunlight in summer. (AMAP 2011a.)
Simulations (Ødemark et al. 2012) indicate that the RF from BC emissions is greatest in early summer. The explanation for this is that the key factor is eventually the intensity of the solar radiation, not the extent of snow and ice cover. That is, even though the greatest possibility for BC deposition is during winter, the concrete absorption of radiation actualizes mainly during summer. Ødemark et al. (2012) crystalize the situation as follows: “There is no sunlight in winter and thus no effect on RF from black carbon on snow, however BC accumulates in the snow over the winter. In spring, when the snow starts to melt, BC reappears and absorbs sunlight, affecting the radiative budget.” In this regard, the most crucial question might concern the possibilities of the transport of BC to the Arctic during winter and mechanisms affecting this domain.

With such peculiar features of BC borne in mind, it is comprehensible that even relatively small increases in BC emissions may have drastic effects within the most vulnerable regions like the Arctic. Furthermore, the Arctic has thus far remained as a rather untouched region, so that the increases of moderate absolute volume may actually result in a notable relative increase. Hence, as the levels of BC emissions and thus BC concentrations in the atmosphere have been low in the Arctic, shipping-based BC is likely to cause increases of a remarkable magnitude.

However, some of the central underlying climatical mechanisms are not very well understood, giving rise to uncertainty in modeling and forecasting the future. For example, the relationship between positive regional RF and the corresponding change in surface air temperatures is unresolved, as some examinations imply that positive RF in the Arctic eventually leads to a cooling effect in the same region (see Shindell & Faluvegi 2009 for details). However, the significance of vertical distribution has to be taken into account, as “the impact of Arctic BC on Arctic surface temperature depends strongly on the altitude of imposed forcing” (Flanner 2013). Regardless of such issues, there is strong scientific evidence that BC contributes significantly to the warming of Arctic climate and that the locations of BC emission sources have remarkable importance.

5.3.3. Definition and measurement

Defining the BC unequivocally has proven to be a rather difficult task, as it is not comprised of any single combination of elements or compounds. The appropriate definition of BC clearly has to be functional, as BC is generally recognized on the basis of its light-absorbing capabilities on one hand and its origin in incomplete combustion on the other.

BC is quite often identified with elemental carbon (EC), a subspecies of PM treated besides organic carbon (OC). For example, in its second greenhouse gas study (Buhaug et al. 2009) IMO speaks of “small unburned carbon particles that are referred to as ‘elemental carbon’ (also known as ‘soot’ when they are visible in size or by their large number)”. However, such definitions are rather inaccurate, leaving thus many essential questions concerning the most important physical properties and the exact measurement technologies unanswered.

There is yet another reason why light-absorbing black carbon is not identical with elemental carbon. As elemental carbon and organic carbon are distinguishable by chemical analysis, elemental carbon and black carbon cannot be used as synonymous expressions, since there are eventually components of organic carbon that absorb light (Jalkanen et al. 2012).

IMO has however been continuously working on more accurate definition of BC, and the following has been proposed to IMO by the Institute of Marine Engineering, Science and Technology (IMarEST):

“Black Carbon (BC) is strongly light-absorbing carbonaceous material emitted as solid particulate matter created through incomplete combustion of carbon-based fuels. BC contains more than 80% carbon by mass, a high fraction of which is sp² bonded carbon, and, when emitted, forms aggregates of primary spherules between 20 and 50 nm in aerodynamic diameter. BC absorbs solar radiation across all visible wavelengths and freshly emitted BC has a mass absorption efficiency of 5 m² g⁻¹ at the mid-visible wavelength of 550 nm. The strength of this light absorption varies with the composition, shape, size distribution, and mixing state of the particle.” (IMO 2011b, 2–3.)

The IMO’s Sub-Committee on Bulk Liquids and Gases (BLG) has subsequently presented four different definitions—Elemental Carbon (EC), equivalent Black Carbon (eBC), refractory Black Carbon
(rBC), and Light Absorbing Carbon (LAC)—of which two most operable have been selected for further refining (IMO 2014). The current alternatives for BC definition are:

1. Equivalent Black Carbon: “Black Carbon is defined as equivalent Black Carbon (eBC) derived from optical absorption methods that utilize a suitable mass-specific absorption coefficient” (IMO 2014, 4).

2. Light Absorbing Carbon: “Black Carbon is defined as light absorbing carbonaceous compounds (LAC), resulting from the incomplete combustion of fuel oil” (IMO 2014, 5).

The possibility of performing BC emission measurements both accurately and cost-effectively has been central issue concerning the development of the appropriate BC definition. Despite the consensus on the pragmatic nature of the definition—IMO member states generally agree that at least the preliminary definition may be purely technical and thus not strictly scientific—some disagreements over possible measurement technologies have hindered the overall process. (IMO 2014.)

With regard to the choice between eBC and LAC, it is noteworthy that “whilst eBC is a subset of LAC, not all measurement methods for eBC are applicable to LAC” (IMO 2014, 4). This stems from the fact that the LAC definition is actually broader than the current conception of BC, covering all types of carbonaceous material—including organic brown carbon. Such broadness can be seen as an advantage, if the target is to reduce the short-term climate forcing effect of all light absorption compounds in the Arctic. On the other hand, such a broad definition might only distract the work currently focusing more purely on BC. (IMO 2014.)

In addition, of the four currently most promising measurement methods (Filter Smoke Number, Multi Angle Absorption Photometry, Photo-Acoustic Spectroscopy, and Laser Induced Incandescence) applicable to BC, each supports eBC, whereas only one is suitable for LAC. A constraint of such importance may notably impede the approval of LAC as BC definition, but the issue is rather complex, as the eventual choice of measurement method should also take future possible developments into account. In other words, the consideration of the definition should not be strictly limited to currently existing measurement methods. (IMO 2014.)

There are certain technical limitations in the current instruments available for BC measurements. In general, instruments are either capable of speciating particle mass or of directly measuring light absorption, but performing both of these functions at once is difficult or unfeasible. Hence, assumptions regarding the relationship between particle mass and light absorption (mass absorption efficiency) are needed, and the possible application of inappropriate values introduces significant uncertainties. Producing better estimates of mass absorption efficiency by parallel measurements of light absorption and mass however reduces the uncertainty. (IMO 2011b.)

All the possible measurement methods can be roughly divided into two subcategories, namely into filter-based and in situ methods. IMO describes the methods and their essential features as follows:

“Filter-based methods involve collecting particles on quartz or Teflon filter media, where they are weighed to obtain mass density, or where light absorption is derived from the attenuation of light transmitted or reflected from the loaded filter. Filter sampling is relatively simple, low cost, and widely used. However, measurements are affected by interaction with the filter that causes changes in particle size and morphology. Corrections can be made using assumptions about the effects of filter media and the nature of the particle sample.” (IMO 2011b, 3.)

“An in situ method measures particles suspended in air. This removes uncertainties inherent in artifact corrections needed for filter-based methods. Light absorption can be measured via indications of temperature change after exposure to light. This includes temperature change via the pressure disturbance of surrounding air, the change in the refractive index, or thermal radiation in the visible or near-visible spectrum. Absorption can also be measured by the difference method (i.e. the extinction minus scattering coefficient). The application of these in situ techniques is less widespread due to their higher cost and complexity.” (IMO 2011b, 4.)
5.3.4. The generation of BC emissions

BC is an inevitable by-product of combustion processes, originating in the incompleteness of combustion. The conditions in which the combustion occurs have thus great significance for the generation of BC emissions, and by idealizing the conditions the amount of BC emissions may be minimized. Engine type and load levels as well as fuel quality have also notable effect, implying that there are various factors to be taken into account when assessing feasible abatement methods and technologies. These issues will be discussed here in detail, in order to gain appropriate foundations for managing future projections concerning BC emissions globally and in the Arctic.

In general, engines are tuned for maximum operating speed at full engine load, and operation at lower loads creates a less efficient combustion process, leading presumably to increases in emissions such as BC (Lack & Corbett 2012). Hence maintaining designed load levels even in situations demanding less engine output power is advisable. The role of multi-engine and combined diesel-electric setups is crucial in this regard, as lower performance may be attained by turning temporarily unnecessary engines off (see e.g. Jalkanen et al. 2012 for more details). In Fig. 33 the results of a meta-analysis of studies examining the relationship between the emission factor of BC and ship engine load is presented. Though there is notable variation in results, it is evident that engines are usually performing most ideally at full loads.

For example, when ships reduce load from 100% to 25% (in order to reduce fuel consumption) without re-tuning the engine, the BC emissions become threefold. At lower loads, the BC emissions increase even more, as the emission factor of BC may be up to 6.5 times the ideal. When the increased emission factors are combined with the reduced fuel consumption associated with lower loads, absolute emissions of BC nevertheless increase by 15–40% down to 25% load. Below 25% load, absolute emissions of BC increase by 100–150%. (Lack & Corbett 2012.)

High-temperature and high-pressure engines—like large marine engines—are in principle fairly efficient at converting fuel carbon to CO₂, generating thus less carbon based PM emissions such as BC. Such hypothesis is confirmed by statistics presenting average emission factors by engine type, as smaller medium-speed diesel (MSD) engines produce more than twice the amount of BC emissions per kg of fuel compared to larger slow-speed diesel (SSD) engines. (Lack et al. 2009.)

Fuel quality affects both the amount and the composition of the emissions from combustion. Residual fuels—commonly used in large marine engines—tend to contain high levels of sulfur, heavy metals, ash (non-combustible inorganic material) and high molecular weight aromatic hydrocarbons. Such impurities (with the exception of heavy metals) may result in a slower and delayed combustion, which in part gives rise to increased BC emissions. (Lack & Corbett 2012.)

However, the relation between fuel quality and BC emissions is not quite straightforward, as the effects of fuel sulfur content are open to dispute, and heavy metals are known to create localized hot-spots within the flame and thus catalyze the combustion of BC (Lack & Corbett 2012). For example, there does not seem to be any distinguishable linear dependence between fuel sulfur content and the emission factor of BC, but merely an inverse one. However, according to Lack et al. (2009) such relationship is a secondary one, as BC emissions are so heavily dependent on engine type.

Furthermore, a study by Ristimäki et al. (2010) indicates that low-sulfur fuel actually produces notably more BC emissions than high-sulfur fuels, the especially at high engine loads. The possible explanation might relate to differences in BC oxidation temperatures according to fuel sulfur content, and the catalyzing effects of heavy metals within the fuel (Ristimäki et al. 2010). A meta-analysis by Lack & Corbett (2012) however indicates that such observations appear to be opposite to the majority of the
trends, and when the inconsistent data is removed from the statistical examination, the average BC emission factor decreases as much as 45% (at 100% engine load).

5.3.5. Methods and technologies for gaining abatements

On the basis of these findings, potential technological and operational measures for the abatement of BC emission may be assessed. To be sure, the most efficient alternative is likely to be a combination of different single solutions. In general, the possible options for reducing emissions from shipping may be divided into four fundamental categories. According to IMO (Buhaug et al. 2009), the categories are:

- Improving energy efficiency: doing more useful work with the same energy consumption (the design and the operation of ships).
- Using renewable energy sources (e.g. the wind and the sun).
- Using fuels with less total fuel-cycle emissions per unit of work done (e.g. biofuels and natural gas).
- Using emission-reduction technologies: achieving reduction of emissions through chemical conversion, capture and storage, and other options.

Focusing on BC emissions, an IMO-related report (Lack et al. 2012) compiles a list of most promising abatement technologies. However, the analysis provided in the report does not take only BC emission issues into account, but it includes a number of different factors related to the reasonability and feasibility of the abatement options. For example, the possible consequences to other species of emissions (CO₂, NOₓ and SOₓ) as well as the commercial availability and the implementation time of the technologies comprise a substantial part of the examination as a whole. Based on the comparison, the following seven options involve most potential with regard to the abatement of BC emissions:

- EEDI (Energy Efficiency Design Index)
- Slow steaming (with de-rating of the engines)
- Water in Fuel Emulsion (WiFE)
- Heavy Fuel Oil (HFO) distillate
- Liquefied Natural Gas (LNG)
- Diesel Particulate Filters (DPF)
- Exhaust Gas Scrubbers (EGS)

The EEDI refers to the system of improved fuel efficiency through vessel redesign. EEDI is adopted by IMO, and it requires graduated improvements⁹ to the energy efficiency of new build ships. The adjustment of the relevant details is left to the designers, builders and owners of the new ships, which is presumed to encourage them to find new solutions in attaining the improved efficiency. The new solutions are however likely to concern issues related to propellers, hull design and cleaning, aerodynamics, and the weight of the ship. (Lack et al. 2012.)

Slow steaming means a reduction from full ship speed to a lower speed, aiming at reduced fuel consumption. As fuel consumption increases as a cubic function of vessel speed, the attained fuel savings may be significant even with relatively moderate decreases in speed. For example, a 10% decrease in speed will lead to a decrease of approximately 27% in fuel consumption. However, since lower speeds means increased transit times and thus reduced transportation capacities, additional ships are needed in

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⁹ EEDI requires reductions in levels of CO₂ per tonne-mile compared to a 2013 baseline value (i.e. EEDI reference line, determined by the type and DWT of each vessel). The rate of reduction is 10% from the beginning of 2015, increasing to 20% and 30% from 2020 and 2025, respectively. (IMO 2011a.)
order to maintain the level of capacity. Hence the reduction of 10% in speed results eventually in a 20% reduction in fuel consumption. (Lack et al. 2012.)

As mentioned before, running the engine at relatively low loads—for example, due to decreased cruising speed—alters the combustion conditions harmfully and causing increases in the emissions levels. Thus the most efficient implementation of slow steaming operating mode involves the re-tuning or de-rating of the engine. With the utilization of real-time tuning, slide valves and de-rating—that is, technologies that reduce the fuel consumption in themselves—ideal combustion conditions may be attainable at all load levels, at least in theory. Slow steaming, combined with engine de-rating, may reduce BC emissions up to 30%. (Lack et al. 2012.)

Water in fuel emulsion is a fuel treatment method, which improves combustion by increasing the atomization of fuel, resulting in remarkable emission reductions. WiFE appears to be particularly efficient with regard to BC emissions, leading potentially up to 90% reductions. The effects of WiFE to fuel consumption are yet uncertain, as both increases and reductions have been reported. Moreover, engine and fuel type as well as additional engine adjustments are likely to have notable significance to the efficiency of WiFE, and further studies are thus needed. (Lack et al. 2012.)

Heavy fuel oil distillates refer to improving the quality of fuel used in marine engines. As mentioned before, the HFO currently in use is rather impure, containing high concentrations of sulfur, heavy metal, inorganic ash and aromatic hydrocarbons. The concomitant BC emissions from combustion are a function of both fuel quality and engine load levels, implying that the relationship is not unequivocal. Despite the substantial uncertainty in this respect, improving HFO quality is likely to result in significant reductions also in BC emission levels. Relying in part to the findings of forthcoming studies, Lack et al. estimate the reduction potential to be as much as 80%. (Lack et al. 2012.)

Liquefied natural gas is an alternative to traditional

<table>
<thead>
<tr>
<th>Abatement measure</th>
<th>BC reductions (%)</th>
<th>CO₂ reductions (%)</th>
<th>Technology maturity</th>
<th>Implementation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEDI (Energy Efficiency Design Index)</td>
<td>30.0</td>
<td>30.0</td>
<td>Commercially available</td>
<td>Over 10 years</td>
</tr>
<tr>
<td>Slow steaming (with de-rating of the engines)</td>
<td>15.0</td>
<td>18.5</td>
<td>Commercially available</td>
<td>1-5 years</td>
</tr>
<tr>
<td>Water in Fuel Emulsion (WiFE)</td>
<td>70.0</td>
<td>0.0</td>
<td>Commercially available</td>
<td>Less than a year</td>
</tr>
<tr>
<td>Heavy Fuel Oil (HFO) distillate</td>
<td>52.0</td>
<td>7.0</td>
<td>Commercially available</td>
<td>Less than a year</td>
</tr>
<tr>
<td>Liquefied Natural Gas (LNG)</td>
<td>93.5</td>
<td>22.5</td>
<td>Commercially available</td>
<td>1-5 years</td>
</tr>
<tr>
<td>Diesel Particulate Filters (DPF)</td>
<td>85.0</td>
<td>-3.0</td>
<td>Demonstrations performed</td>
<td>1-5 years</td>
</tr>
<tr>
<td>Exhaust Gas Scrubbers (EGS)</td>
<td>60.0</td>
<td>-3.0</td>
<td>Commercially available</td>
<td>Less than a year</td>
</tr>
</tbody>
</table>

Table 7. The most promising black carbon abatement measures on the basis of the BC-specific efficiency, technology maturity and implementation time, and effects on other species of emissions. The indicated values are averages of lower and upper boundaries of abatement potential, and may thus differ from the maximum values discussed in the section 5.3.5. Data source: Lack et al. 2012.

Fig. 34. The cost effectiveness of selected black carbon abatement technologies in scenarios with various marine diesel oil (MDO) price levels (Low: $320 per ton, Medium: $1 012 per ton, High: $1 213 per ton). “Negative cost” indicates that the implementation of such technology is profitable in its own right due to an improvement in vessel overall efficiency. WiFE stands for Water in Fuel Emulsion, LNG for Liquefied Natural Gas, DPF for Diesel Particulate Filters, SWS for Sea Water Scrubbers, and FWS for Fresh Water Scrubbers. Data source: Lack et al. 2012.
sources of energy in shipping. Switching to LNG cuts PM emissions radically, eliminating them almost entirely. Thus also BC emissions are presumed to practically vanish, though no observation data about emissions from LNG used in ships is available. The appropriate handling of LNG however poses some indisputable challenges to marine infrastructure, as the possibility of leaks is elevated with volatile fuels. (Lack et al. 2012.)

Diesel particulate filters use ceramic or metal filters to remove PM from the exhaust gases prior to eventual emission. The PM accumulates in the filter and may thereafter be combusted using either active or passive processes. Filter technology is however rather sensitive to the fuel quality, posing additional challenges to feasible utilization among marine engines, which commonly use fairly impure heavy fuel oils. Furthermore, when used in engines burning very impure fuels with high sulfur levels, DPFs may actually increase the amount of PM emissions. Due to these issues, the implementation of DPFs depends strongly on the introduction of cleaner fuels. Slight decrease in fuel efficiency is also presumed. Nonetheless, with the switch to better quality fuel oils, DPFs may be very efficient with regard to BC, reaching up to reductions of 99%. (Lack et al. 2012.)

The main function of exhaust gas scrubbers has been to remove SO₂ from exhaust gases, particularly in situations where heavy fuel oil is used in sulfur emission control areas. Apart from this, scrubbers also decrease the amount of other gas and particle pollutants fairly effectively. Scrubbers can use either seawater (open loop) or freshwater (closed loop), and the alternatives are presumed to have same level of efficiency. The usage of internal freshwater cycle however demands some additional technology installed, raising thus the overall costs of the solution. The efficiency of both seawater and freshwater scrubbers (SWS and FWS) is greatest in the case of high sulfur fuel, resulting in reductions of even 70% in BC emissions. (Lack et al. 2012.)

The most important features of each option are presented in Table 7. Also the effects on CO₂ emission levels as well as few comments on the maturity and implementation time of each technology are explicated. To be sure, the implementation of different abatement technologies causes additional expenditures to marine industry, and the cost effectiveness per mass unit of BC also varies remarkably among the alternatives. The Lack et al. study (2012) includes an approximate calculation concerning the cost effectiveness\(^{10}\) of above-discussed abatement options; the results are shown in Fig. 34.

5.3.6. Emissions today and tomorrow

The amount of black carbon emissions from shipping and the consequential climate impacts have been in the scope of scientific research lately. Both global and Arctic-specific studies have been carried out, focusing either on current levels (emission inventories) or on probable future levels (emission projections). However, the estimates of the current and forthcoming BC emission levels are based on a multitude of definitions and assumptions. Thus a critical approach is always advisable.

An IMO-related inventory of shipping-based emissions (Corbett et al. 2007) estimates the annual BC emissions from the global maritime activities to be approximately 71 thousand tonnes in 2000—2002. An alternative study (Lack et al. 2008) has produced somewhat higher numbers, ranging from 106 to 160 thousand tonnes in 2001. The best estimate of Lack et al. (2008) for BC emissions from global shipping (133 thousand tonnes per year) amounts to approximately 1.7% of global BC from all sources.

However, the examination in question relies on a relatively broad definition of Light Absorbing Carbon (LAC), so that the results may not be entirely comparable. According to the authors of the study, LAC covers in fact both black carbon and brown carbon, as they both absorb light and thus affect the measurements done by utilizing a photoacoustic technique (Lack et al. 2008). In agreement with this, the emission factors used for LAC are slightly higher on average than the corresponding factors for mere BC in the Arctic-specific analysis of Corbett et al. (2010), for example.

There are various estimates concerning the BC fraction of PM, ranging from less than 5 to more than 40% (Corbett et al. 2010). To be sure, there are numerous factors contributing to the composition of PM emissions and thus the share of BC. For example, engine type and fuel quality influence notably, and the essential roles of the applied BC definition and the measurement technologies chosen according-

\(^{10}\) The assessment is based on estimates of technology installation costs and time, additional operating costs due to possibly increased fuel consumption, and the presumed development of the interest and fuel price levels.
ly must be borne in mind. Hence it is clear that no universal rate is appropriate, and quantifying such is not even reasonable.

According to Corbett et al. (2010), marine activities in the Arctic region produced a grand total of 1.2 thousand tonnes of BC emissions in 2004. This amounts to a share of few percentages of BC from global shipping, depending on the used estimates. Anyway, the relation of magnitudes is clear, and the role of the Arctic shipping is rather minor.

Peters et al. (2011) have also estimated the shipping-based BC emissions in the Arctic, though their study is not all-inclusive, as some sectors of shipping—such as marine activities related to tourism, fishing and local re-supply—are excluded from the numbers. They have evaluated a total amount of 1.2 thousand tonnes in 2004, which is practically same as the estimate of Corbett et al.

Both of the above-mentioned studies include also future projections of the shipping-based emissions in the Arctic, with the share of BC specified. The projections are based on the assumptions explained earlier (in the section 4.4 in detail, and in section 5.1.2 more briefly), so that the results must be treated accordingly. In addition to the set of scenarios already introduced, Corbett et al. (2010) present also an option of maximum feasible reduction with respect to BC emissions (MFR). On the grounds of a feasible combination of improvements in technology performance and the implementation of certain abatement methods, BC emissions are assumed to decrease altogether 70 % in MFR. By including the

Fig. 35. The projected Arctic black carbon emissions in High Growth (top line images) and Business As Usual (bottom line images) scenarios. The predicted effects from implementation of abatement technology are presented in Maximum Feasible Reduction scenario (MFR, right-hand images). Source: Corbett et al. 2010.
MFR option in their study, Corbett et al. enable a rather efficient comparison of different possible future developments, and thus the evaluation of the potential effects of unrestrained BC emissions.

In the Business As Usual scenario, shipping-based BC emissions in the Arctic (excluding the share of fishery) are estimated to be 1.4 and 5.0 thousand tonnes in 2050, in MFR and no-control scenario, respectively. In the High Growth scenario, the corresponding amounts soar to 5.0 and 17 thousand tonnes, respectively. The projected BC emissions from Arctic shipping in different scenarios—with and without abatements—are presented in Fig. 35, while the geographical distribution of the projected emissions in 2030 is shown in Fig. 36. (Corbett et al. 2010.)

The grand total of 17 thousand tonnes in the High Growth scenario with no control measures is of very remarkable magnitude, when for example compared to the estimates of current BC emissions from global shipping (that is, 71—160 thousand tonnes). It also means an increase of about 1 800 % in BC emissions from Arctic shipping from the 2004 level. However, the shipping-based BC emissions originating in non-Arctic regions are presumed to increase as well, so that the relative proportion of Arctic emissions remains moderate.

The non-Arctic rates for BC emissions from shipping in 2050 are 393 and 710 thousand tonnes, in BAU and HiG scenarios, respectively (Corbett et al. 2010). Thus the share of Arctic BC emissions is at

![Fig. 36. The geographic distribution of past (2004) (a) and projected (2030) black carbon emissions, both with (c) and without (b) the maximum feasible reduction (MFR) control measures. Source: Corbett et al. 2010.](image-url)
most around 2.5% in 2050—that is, in the no-control HiG scenario. Nonetheless, it must be noted that the approximated amount of 710 thousand tonnes of BC emissions from global non-Arctic shipping in 2050 is in itself susceptible, as it relies on a constant annual growth of 3.3%.

The analysis of Peters et al. (2011) results in more moderate amounts. Their estimate for BC emissions from Arctic shipping (excluding marine activities related to tourism, fishing and local re-supply) in 2050 is 3.0 thousand tonnes, implying an increase of about 150% compared to the 2004 level. In their examination, the BC emission factor is presumed to remain the same, indicating a scenario with no abatement technologies implemented.

According to Winther et al. (2014), the BC emissions from Arctic shipping (excluding traffic on diversion routes) are projected to rise from 1.58 thousand tonnes in 2012 to 1.84 thousand tonnes in 2050, implying thus an increase of 16%. The share of traffic using diversion routes in 2050 is presumed to increase the BC emission levels about 87%. Hence, the total BC emissions from Arctic marine activities are estimated to increase altogether 118% from the 2012 level to 3.45 thousand tonnes in 2050.

Yet it must be emphasized that the rates from different studies are based on varying assumptions and definitions, so that the results are not entirely commensurable. For example, there is no established and thus unequivocal geographical definition of Arctic waters, and the coverage\textsuperscript{11} of the inventories and projections varies. Despite such remarkable difficulties, a summarizing compilation of both estimated current and projected future emissions is presented in Fig. 37.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig37}
\caption{An overview of estimated current and projected future SO\textsubscript{2}, NO\textsubscript{x} and BC emissions from shipping in the Arctic area according to different studies. With regard to the present day estimates, the inventory year is different in the Winther et al. 2014 study. These numbers include possible diversion traffic, whereas fishing vessels are excluded systematically. In addition to this, the numbers of the Peters et al. 2011 study exclude marine activities related to tourism and local re-supply. Data sources: Corbett et al. 2010, Peters et al. 2011 and Winther et al. 2014.}
\end{figure}

5.3.7. Probable implications of BC emissions

The IPCC (2013) has evaluated the effects of BC emissions in global scale. The RF from direct aerosol forcing has been divided into two shares according to the origin of the emissions. The sources are grouped as anthropogenic and natural sources: the first group covers emissions from fossil fuel and biofuel burning, whereas the latter covers biomass burning such as wildfires and forest fires.

\textsuperscript{11} Certain vessel types are often excluded from the assessments, mainly due to methodological reasons. For example, the share of fishing vessels may not be included, as the emissions from fishing vessels are based on operating activity instead of number of trips.
The IPCC's (2013) estimates of corresponding RFs are $+0.4\ (+0.05\ to\ +0.8)\ W\ m^{-2}$ and $+0.2\ (+0.03\ to\ +0.4)\ W\ m^{-2}$, respectively. The additional RF from deposits to snow and ice is estimated to be $+0.04\ (+0.02\ to\ +0.09)\ W\ m^{-2}$. The RF from BC-related aerosol-cloud interactions has not been assessed separately, so corresponding rates are not available for comparison. Altogether, these rates are of considerable magnitude when compared, for example, to CO$_2$, the single most significant greenhouse gas, for which alone the RF is $+1.82\ (+1.63\ to\ +2.01)\ W\ m^{-2}$.

The above-mentioned rates are global averages, and the BC emissions are presumed to have much greater effects when considering local regions with peculiar features. Especially the effect of BC deposited to snow and ice has notable additional bearings in the Arctic, where relatively large parts of total area are covered with snow and ice. Also, due to the remote location of the Arctic region, the BC emissions from Arctic shipping are likely to have particular importance to the local concentrations and radiative budget.

Fig. 38. The estimated effects of black carbon emissions from Arctic shipping in 2004: the contribution to tropospheric column of black carbon [$\mu g\ m^{-2}$] (left-hand image), and the radiative forcing from black carbon deposited to snow [mW m$^{-2}$] (right-hand image). Source: Ødemark et al. 2012.

Fig. 39. The seasonal normalized radiative forcing for black carbon emission from Arctic shipping in 2004. Left-hand image (a) depicts the situation in wintertime, and right-hand image (b) in summertime. Source: Ødemark et al. 2012.
As was the case with other air pollutants, the two above-discussed studies (Corbett et al. 2010 and Peters et al. 2011) have given rise to further analysis of the climate impacts from shipping-based black carbon emissions, too. Particularly effects on concentration levels and radiative budget are examined, and, with regard to BC, the possibility of deposition to snow and ice cover is of additional interest. In this section, the outcomes of a number of such refined and profound studies are presented.

The study of Ødemark et al. (2012) discusses the effects of present-day (2004) BC emissions from shipping (and petroleum activities) in the Arctic region on the atmospheric BC concentrations and the corresponding radiative forcing, based on the inventories in Peters et al. (2011). Due to the rather short lifetime of BC (on the order of days), the influences are most substantial near emission locations, as shown in Fig. 38.

According to Ødemark et al. (2012), the average atmospheric burden of BC emissions from Arctic shipping in the northernmost latitudes (60—90°N) is 0.38 μg m⁻². The consequential radiative forcing is 0.60 mW m⁻², and the additional forcing from BC deposited to snow is 0.47 mW m⁻². These numbers imply a total RF of about 1 mW m⁻² from Arctic shipping, which can be compared to the RF of 49 mW m⁻² from the CO₂ emissions of global shipping in 2007. The geographic distribution of radiative forcing from BC on snow is presented in Fig. 38. It is noteworthy that the corresponding rates for BC emissions from Arctic petroleum activities are 4.1 μg m⁻², leading to a forcing of 6.5 mW m⁻², with an additional 20 mW m⁻² from deposition to snow. Such difference in the scale implies that the current levels of BC emissions from mere Arctic shipping are rather moderate after all, and that the geographic extent of the shipping-related sources is fairly limited at present.

Ødemark et al. (2012) have also examined the normalized forcing of BC—that is, the radiative forcing per unit of BC burden change—in the Arctic. The level of normalized forcing depends mainly on the latitude and the timing of emissions, and the highest possible normalized forcing occurs in the high latitudes during the most intense insolation. This is clearly visible in Fig. 39, which illustrates the normalized forcing for BC both in winter and in summer. The difference in normalized forcing between winter-

![Fig. 40. The projected black carbon concentration changes until summer 2030 and the consequent radiative forcing, in scenarios with minimum (MFR, left-hand images) and maximum (HIGH, right-hand images) emissions from shipping. Source: Dalsøren et al. 2013.](image-url)
time (little or no sunlight) and summertime (more or less constant sunlight) is remarkable particularly in the Arctic, manifesting the peculiarity of Arctic climatic mechanisms.

Dalsøren et al. (2013) examine the changes in surface concentrations and radiative forcing stemming from shipping-based BC emissions until 2030, utilizing the projections of Corbett et al. (2010). Also the possible effects resulting from the implementation of abatement technology—included in the MFR scenario of Corbett et al.—are taken into account, as relevant comparisons between no-control High Growth (HiG) and MFR Business As Usual (BAU) scenarios are performed, crystallizing the differences between extreme alternatives.

In the MFR BAU scenario, there are in fact decreases in BC emissions within regions of busy internal traffic, but corresponding increases in the regions with diversion traffic. In the no-control HiG scenario there are increases of more than 50 % in BC levels all over the Arctic, focusing on the vicinity of diversion routes. With regard to the radiative forcing, BC has undeniably more significance in the Arctic compared to the rest of the world. (Dalsøren et al. 2012.)

The variance between seasons is also very clearly distinguishable, mainly due to accumulated deposition of BC to snow during the winter. For example, in the no-control HiG scenario, the RF from BC on snow is about twenty-thirty times higher in summer (~10 mW m⁻²) compared to the winter (~0.4 mW m⁻²). The total RF from BC (both aerosol and deposition effects) is about 60 % lower in the MFR BAU than in the no-control HiG scenario. The comparison between scenarios can be found in Fig. 40, in which the concentration changes until summer 2030, and the consequent radiative forcing are presented. (Dalsøren et al. 2012.)

The deposition of BC in the Arctic has been subject to a more elaborate analysis, too. For example, Browse et al. (2013) have assessed the origin of the Arctic BC depositions, clarifying the role of Arctic shipping and thus evaluating the efficiency of the measures taken within the field of marine industry.

The outcomes of the assessment imply that even in the scenario with most intense BC emissions—the no-control HiG scenario from Corbett et al. (2010)—the proportion of Arctic shipping is eventually rather small, as the BC emissions from Arctic shipping lead to a contribution of merely 0.7 % to the total BC deposition north of 60 °N in 2050. Despite this, regional impacts are projected to be much more considerable, reaching up to 15 % over the west coast of Greenland and the Bering Sea. However, it must be noted that such numbers are valid only if the levels of the extra-Arctic shipping emissions and the global non-shipping emissions remain unaltered, which is rather unlikely. (Browse et al. 2013.)

The overall message of the Browse et al. (2013) study is that while the reductions in BC emissions from Arctic (and non-Arctic) shipping are likely to have notable regional effects, such reductions simply are not enough to decrease the rate of Arctic BC deposition. In fact, the projected increases in BC emissions from Arctic shipping are relatively so small that their influences to the Arctic-wide average are likely to remain unmeasurable due to the enormous scale of natural emission variability from wildfires, changes in transport efficiency, and reductions in lower latitude anthropogenic emissions. The only effective solution to attain Arctic BC deposition reductions appears to be setting controls over distant stationary sources, reducing thus the transport of BC to the Arctic.

Similar issues are discussed in the study of Winther et al. (2014), which also is based on work of Corbett et al. (2010). Utilizing the growth rates of BAU scenario from Corbett et al., they produce spatial distributions of BC emissions in 2012 and 2050. On these grounds, evaluations of BC concentrations and depositions are made, for both 2012 and 2050.

The increased emissions (see section 5.3.6) have impacts on the concentration and deposition of BC. However, as was the case with Browse et al. (2013), also the results of Winther et al. (2014) show that the contribution of BC emissions from Arctic shipping to Arctic-wide averages is yet moderate, reaching to increases of 3.6 % in BC concentration and 1.0 % in BC deposition in summertime 2050. Nevertheless, along the diversion routes, local BC concentrations are projected to rise over 80 % due to increased Arctic shipping. Similarly, over the ocean east of Greenland and in the High Arctic, the levels of BC deposition are estimated to be 5 % higher as a result of BC from Arctic shipping. The comparison between 2012 and 2050 with regard to the spatial distribution of BC emissions, BC concentrations as well as BC deposition is presented in Fig. 41.
Fig. 41. The comparison between 2012 (left-hand images) and 2050 (right-hand images) with regard to the spatial distribution of BC emissions (top line images), BC concentrations (middle line images), and BC deposition (bottom line images). Source: Winther et al. 2014.
6. Conclusions

Due to the Arctic climate change and the related diminishing of Arctic sea ice cover, the general conditions for Arctic shipping are changing. The retreat of Arctic sea ice opens up new routes for maritime transportation, both trans-Arctic passages and new alternatives within the Arctic region. Hence the amount of Arctic shipping is presumed to increase.

Despite the maritime conditions in the Arctic are undeniably changing, certain characteristic features of the Arctic waters will remain unaltered. Hence the sailing conditions of the Arctic region will not be comparable to those of blue waters at least in the near future, and open-water vessels are very likely to encounter serious hindrances when operating in the Arctic. In general, as an ever larger fleet with varying standards of equipment will be exposed to the harsh conditions of the Arctic, a considerable statistical risk of humanitarian and environmental disasters follows.

The increase in Arctic shipping will also lead to an increased amount of emissions. The increased emissions may have remarkable and unpredictable influences to the particularly sensitive Arctic environment. With regard to emission species, especially black carbon is presumed to have climatic significance within the Arctic context. Black carbon absorbs solar radiation very effectively, and when deposited to snow or sea ice cover, it may notably alter the radiative equilibrium of the Arctic region.

The International Maritime Organization (IMO) has had a central role in cutting down emissions from marine activities. However, with regard to black carbon, there are some disagreements among IMO member states that hinder implementing regulations and thus gaining abatements. Above all, defining black carbon unequivocally has proven to be a rather difficult task, and the related selection of approved measurement technologies has been a rather time-consuming process.

Altogether, assessing the climate impact from black carbon emissions originating in Arctic shipping is a very timely task, as the current volume of Arctic shipping and the related emissions is yet rather moderate, but substantial growth is expected already in the near future. Hence the disputes within IMO must also be resolved as soon as possible, so that the undesired effects of Arctic shipping emissions can be minimized.

There is a wide range of methods and technologies for gaining black carbon emission abatements, and the most efficient alternative is likely to be a combination of different single solutions. However, the reductions in black carbon emissions cannot be assessed as a separate issue, and the consequences of different abatement measures to other species of emissions have to be taken into account right from the beginning.

Many of the solutions aiming at reductions in nitrogen and sulfur oxides as well as carbon dioxide, for example, cut down the black carbon emissions as well, though this is not always the case. In general, it is the joint effect on every different emission species that counts, but with regard to certain specific regions—such as the Arctic—the significance of apparent local climate impacts due to certain specific emission species—such as black carbon—may alter the overall situation substantially.

In conclusion, despite the fact that reductions in locally affecting short-lived emissions may comprise an effective measure to gain relatively fast response, the only way to gain long-term climate change mitigation goals is to continue pursuing abatements of carbon dioxide and other long-lived greenhouse gas emissions. Vice versa, since reducing emissions of long-lived greenhouse gases will have an effect only on longer time scales, cutting down black carbon and other short-lived emissions can effectively help reducing near-term global warming and its impacts, particularly in regions most vulnerable to climate change—such as the Arctic.
**Arctic Shipping Emissions in the Changing Climate**

Reports of the Finnish Environment Institute 41/2014

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Sammandrag
På grund av den arktiska klimatförändringen och den relaterade minskning av arktiska havsisen, ska de allmänna villkoren för arktiska sjöfarten förändras. Reträtt av den arktiska havsisen öppnar nya vägar för sjötransporter, både trans-arktiska passager och nya alternativ inom den arktiska regionen. För den skull mängden arktiska sjöfarten antas öka.
Trots den observerade utvecklingen, kommer förhållandena i den arktiska regionen förblivna utmanande. Särskild uppmärksamhet kommer att krävas även i framtiden när det gäller den lämpligheten av besättningen, flottan och annorlunda infrastruktur.
Utöver andra uppenbara utmaningar och risker kommer ökningen i arktiska sjöfarten leda till en ökad mängd utsläpp. De ökade utsläpp kan ha betydande och oförutsägbara inverkan på den särskilt ömtåliga arktiska miljön.
Bland olika sorter av utsläpp, antas speciellt black carbon ha klimatisk betydelse i den arktiska sammanhang. Black carbon absorberar solstrålning mycket effektivt, och när avlagras på snö eller havsisen kan det betydligt ändra strålningsbalansen i den arktiska regionen. Den ökade arktiska sjöfarten producerar utsläpp av black carbon, vars klimateffekter examineras i denna rapport.

Nyckelord
Arktisk sjöfarten, Arktisk klimatförändring, Fartyngutsläpp, Black carbon
Due to the Arctic climate change and the related diminishing of Arctic sea ice cover, the general conditions for Arctic shipping are changing. The retreat of Arctic sea ice opens up new routes for maritime transportation, both trans-Arctic passages and new alternatives within the Arctic region. Hence the amount of Arctic shipping is presumed to increase.

Despite the observed development, the sailing conditions in the Arctic waters will remain challenging. Thus particular attention will be required also in the future with regard to crew, fleet and other infrastructural issues.

In addition to other apparent challenges and risks, the increase in Arctic shipping will lead to an increased amount of emissions. The increased emissions may have considerable and unpredictable influences to the particularly sensitive Arctic environment.

With regard to emission species, especially black carbon is presumed to have climatic significance within the Arctic context. Black carbon absorbs solar radiation very effectively, and when deposited to snow or sea ice cover, it may notably alter the radiative equilibrium of the Arctic region. The increased Arctic marine activities produce black carbon emissions, whose climate impacts are assessed in this report.

**Keywords**

Arctic shipping, Arctic climate change, Shipping emissions, Black carbon