PRIME MINISTER'S OFFICE
FINLAND

The effects of climate change and abatement policies on the value of natural resources in Northern Europe and in the Arctic Sea area

Prime Minister's Office Reports 1/2011

The effects of climate change and abatement policies on the value of natural resources in Northern Europe and in the Arctic Sea area

Prime Minister's Office Reports | 1/2011

Publisher PRIME MINISTER’S OFFICE	DESCRIPTION 18 January 2011

Authors
Anatoly Shvidenko (shvidenk@iiasa.ac.at)
Zbigniew Klimont (klimont@iiasa.ac.at)
Kaarle Kupiainen (kupiain@iiasa.ac.at)
Shilpa Rao (rao@iiasa.ac.at)
Dmitry Schepaschenko (schepd@iiasa.ac.at)
With contributions from:
Valery Karklin (karklin@aari.nw.ru)
Alexander Yulin (icefor@aari.nw.ru)
Valentin Strakhov (strakhov48@mail.ru)

Type of publication
Report

Commissioned by
Prime Minister's Office

Date of appointment

Title of publication
The effects of climate change and abatement policies on the value of natural resources in Northern Europe and in the Arctic Sea area

Abstract

The impact of the climate on the Arctic plays a crucial role for Finland’s, as well as other Nordic countries’ current and future climatic conditions. Far-reaching and multi-faceted changes are taking place in the Arctic, which have profound consequences for the region’s economic and political significance in international relations. The review analyses the effects of climate change and likely climate abatement policies on the accessibility and value of natural resources in Northern Europe in the Arctic Sea area and on the logistical position of Northern Europe with a special emphasis on Finland.

Keywords
Arctic, climate change, natural resources

Name of series and number of publication Prime Minister’s Office Reports 1/2011		**ISSN**	**ISBN (print)**
Number of pages 93	**Language** En	**Confidentiality rating** Public	**ISBN (PDF)**
Publisher Prime Minister's Office Publication as a PDF: www.vnk.fi/english Further information: julkaisut@vnk.fi		**Layout** Prime Minister's Office/Policy-analysis Unit	
Distribution and sales julkaisut@vnk.fi		**Printed by** Prime Minister's Office	

CONTENTS

SUMMARY IN FINNISH

Viime vuosikymmeninä sekä Pohjoisen jäämeren rannikkovaltiot että sisämaavaltiot ovat osittaneet kasvavaa kiinnostusta arktista aluetta kohtaan. Joidenkin arvioiden mukaan arktisella alueella voi olla jopa 90 miljardia tynnyriä öljyä ja noin kolmasosa maailman kartoittamattomista maakaasuvaroista. Rannikkovaltiot (Kanada, Norja, Tanska, USA ja Venäjä) ovat lisänneet pyrkimyksiään laajentaa toimivaltaansa yksinomaisten talousvyöhykkeidensä ulkopuolisille merialueille, joihin Arktisen neuvoston kolmen muun jäsenvaltion (Islannin, Ruotsin ja Suomen) kiinnostus myös kohdistuu. Myös arktisen alueen ulkopuoliset maat (mm. Euroopan unioni, Kiina) ovat osoittaneet lisääntyvää kiinnostusta aluetta kohtaan. Ihmisen toiminnasta aiheutuvien kielteisten vaikutusten vähentämiseksi arktisella alueella keskeisenä tavoitteena on arktisen ympäristön hoito ja ennen kaikkea öljyvahinkojen estäminen meri- ja ranta-alueilla samoin kuin ilmansaasteiden, mm. pysyvien orgaanisten yhdisteiden, torjunta. Arktisen alueen ympäristönsuojelua varten ei ole vielä kehitetty omia erityisiä määräyksiä. Tässä suhteessa YK:n merioikeusyleissopimus voisi toimia yleisenä kehyksenä.

Tällä hetkellä arktinen alue on tulevan kehityksensä taitekohdassa. Meillä näyttäisi olevan kaksi vaihtoehtoa – joko laaja kansainvälinen yhteistyö, joka tähtää ihmisen ja luonnon rinnakkaiseloon, herkän arktisen ekosysteemin kestävään kehitykseen ja lukuisten alkuperäiskansojen elämänlaadun parantamiseen, tai uusi alueellinen "kylmä sota" – oikeudelliset ristiriidat, lisääntyvät kiistat alueen hallinnasta ja sotilaallinen läsnäolo. Valitsemamme tie määrittelee tämän hyvin mutkikkaan, haavoittuvan ja dynaamisen alueen tulevan kohtalon. Vaikka arktisen alueen täydellinen demilitarisointi onkin epätodennäköistä, Venäjän ja Norjan hiljattain aikaansaama rajasopimus pitkään kiistellyllä Jäämeren alueella on askel oikeaan suuntaan kohti uutta kansainvälistä sopimusta, jonka avulla voitaisiin ratkaista Barentsinmeren merkittävien öljy- ja kaasuvarantojen hyödyntäminen ja arktisen alueen kansainvälinen hallinto.

Arktisen alueen ilmastolla on merkittävä vaikutus Suomen ja muiden Pohjoismaiden nykyiseen ja tulevaan ilmastoon. Satelliittikuvista on havaittu, että Jäämeren jääpeite on supistunut 1970-luvun lopulta lähtien. Euraasian pohjoisten merialueiden sulaminen tekee todennäköisesti mahdolliseksi avata lyhyempi laivareitti Euroopan, Aasian ja Tyynen valtameren välille ja hyödyntää arktisen merenpohjan mahdollisesti valtavia luonnonvaroja, mm. öljyä, kaasua, mineraaleja ja kalakantoja. Arktisen alueen laivaväylät saadaan mahdollisesti myös kauppamerenkulun ja matkailun käyttöön. On kuitenkin olemassa monia haasteita, jotka voivat rajoittaa merenkulun tulevaa kehitystä arktisella alueella. Näitä ovat laivaväylien hallinta, keskeisen infrastruktuurin puute ja aluksia koskevien standardien harmonisointi. Esimerkiksi arktisen alueen merenkulun arviointiraportissa (AMSA) (Arktinen neuvosto, 2009) todetaan, että vuonna 2020 suurin osa arktisen alueen liikenteestä kohdistuu edelleen tiettyihin satamiin koko arktisen alueen poikki kulkevan liikenteen sijaan.

Arviot jään sulamisen vauhdista ja laajuudesta eroavat huomattavasti toisistaan: yhtäällä on kansainvälisen ilmastopaneelin IPCC:n neljänteen raporttiin perustuva vakiintunut näkemys, toisaalla venäläisten ja muiden riippumattomien tutkimusryhmien esittämät arviot. IPCC:n ennusteet viittaavat siihen, että jään sulaminen jatkuu koko tämän vuosisadan ja loppukesän jääpeite katoaa lähes kokonaan ennustusjakson loppua lähestyttäessä. Vaihtoehtoisissa laskelmissa (joita on laadittu esimerkiksi Venäjän arktisessa ja antarktisessa instituutissa) ennustetaan, että Jäämeren jääalueen dynamiikka jatkuu vaihtelevana (ilman tiettyä kehitystrendiä). Syynä tähän ovat ensisijaisesti ilmastosyklien ja pitkän aikavälin trendien alueelliset erityispiirteet. Riippumatta siitä, mitkä ennustukset osoittautuvat oikeiksi, meri on lähivuosikymmeninä jään peitossa suuren osan vuotta, ja tämän vuoksi pääsy arktiselle alueelle, muun muassa Luoteisväylälle ja pohjoiselle merireitille, riippuu myös jatkossa jääolosuhteista.

Ikiroudan sulaminen laajoilta alueilta Pohjois-Euraasiasta voisi johtaa hiilipäästöjen (erityisesti metaanin) voimakkaaseen kasvuun. Tämä palautemekanismi voisi kiihdyttää arktisen alueen lämpenemistä merkittävästi ja vaikuttaa maapallon ilmaston toimintaan johtaen päästömääriin, jotka ovat vähintään yhtä suuret kuin tropiikin metsien hävittämisestä nykyisin aiheutuvat päästöt. Lisäksi routakausi lyhenee tämän vuosisadan loppupuolella. Keski- ja Pohjois-Suomessa roudan vuotuinen maksimisyvyys pienenee. Vaikka tämä ei poistakaan rakennusten ja rakenteiden suojaamistarvetta kokonaan, se voi vähentää tätä tarvetta, mikä puolestaan alentaa kustannuksia rakennus- ja kuljetusalalla. Toisaalta roudan vähenemisellä voi olla metsäteollisuuden kannalta kielteisiä vaikutuksia puunkorjuun vaikeutumisen myötä.

Euraasian mantereen pohjoisten alueiden ja niihin (varsinkin lännessä) liittyvien merien uskotaan lämpenevän huomattavasti koko tämän vuosisadan ajan. Tähän liittyy myös sademäärien kasvu. Ilmastonmuutoksella on kuitenkin sekä myönteisiä että kielteisiä vaikutuksia näihin alueisiin. Välittömiä vaikutuksia ovat muun muassa:

- Useisiin eläinlajeihin (jääkarhut, hylkeet, mursut, pohjoiset kauriseläimet ja merilinnut) kohdistuu kielteisiä vaikutuksia ja jopa lajien olemassaoloa koskevia uhkia;
- Suuret metsäpalot ja hyönteisten joukkoesiintymiset tulevat yleisemmiksi ja vaikeammiksi torjua eritoten Pohjois-Aasian itäisillä manneralueilla;
- Ilmaston lisääntynyt vaihtelu vaikuttaa maanpäällisten ekosysteemien elinvoimaisuuteen ja tuottoisuuteen. Kuivilla kesillä ja leudoilla talvilla on silminnähden kielteisiä vaikutuksia ekosysteemeihin. Lämpeneminen vaikuttaa järvien vedenlämpöön ja jäänalaisen ympäristön laatuun, mikä todennäköisesti alentaa vesistöjen ekosysteemien tuottavuutta;
- Merien ekosysteemit ovat myös hyvin haavoittuvia. Lämpötilan kohoamisen ja jääpeitteen vähenemisen vaikutuksesta eri kalalajien levinneisyyden rajat liikkuvat pohjoiseen. Ilmastonmuutos voi johtaa eksoottisten lajien leviämiseen, lisätä kilpailua ja kiihdyttää rehevöitymistä ja saastumista. Joillekin arktisille alueille odotetaan suotuisampia oloja, jotka lisäävät rehuvarantoja, laajentavat tiettyjen kalalajien liikkuma-aluetta, tehostavat kalastusta ja lisäävät arvokkaiden kaupallisten lajien vaellusta;
- Jääpeitteen väheneminen helpottaa pääsyä arktisen alueen mannerjalustoille. Ennustettu ilmastonmuutos ei kuitenkaan vähennä vaarallisia hydrometeorologisia ilmiöitä arktisella alueella vaan ainoastaan jakaa ne uudella tavalla (kovien tuulten nostattamien aaltojen lisääntynyt todennäköisyys, ajojään kulkeutuminen uusille alueille jne.);
- On hyvin todennäköistä, että vaarallisten sääilmiöiden lukumäärä ja voimakkuus lisääntyvät (kovat tuulet, lumimyrskyt, jäiset tiet, merialueiden heikentyvät jäät jne.);
- Tällä vuosisadalla arktisilla rannikkoalueilla koettavia vaikutuksia ovat muun muassa nopeampi merenpinnan nousu (0,18–0,59 m) (IPCC 2007), meren pintalämpötilan kohoaminen, sään ääri-ilmiöiden ja myrskypuuskien lisääntyminen, sademäärissä tapahtuvat muutokset ja meren happamoituminen;
- Vaikutukset koskettavat matkailua, elinolosuhteita ja väestön terveyttä, erityisesti kaukana pohjoisessa asuvien ihmisten keskuudessa;

- Lämmityksen tarve voi vähentyä ja korvautua joissakin tapauksissa suuremmalla jäähdytystarpeella. Lisääntynyt ilmastollinen vaihtelu vaikeuttaa yleiseen lämpenemiseen perustuvien pitkän aikavälin strategioiden saavuttamista ja vähentää näiden strategioiden mahdollisia etuja.

Yleisesti ottaen odotetulla ilmastonmuutoksella on enemmän myönteisiä vaikutuksia Pohjoismaissa (erityisesti Suomessa) kuin Pohjois-Euraasian muilla alueilla. Näitä vaikutuksia voivat olla muun muassa:

- Vuotuisen sademäärän kasvu hyödyttää vesivoiman tuotantoa. Odotettavissa on kuitenkin enemmän vaarallisia tulvia ja ylipäätään voimakkaampia virtauksia, joilla on vaikutuksia maa- ja vesirakennustöihin;

- Ilmastonmuutos avaa uusia mahdollisuuksia Suomen maataloudelle. Lämpimämpi ilmasto pidentää termistä kasvukautta ja nopeuttaa fysiologisia prosesseja. Tämän ansiosta yleisesti kasvatettujen lajien viljelyaloja voidaan laajentaa ja pääasiallisten viljelykasvien satomahdollisuudet paranevat. Myös uusia lajeja päästään viljelemään. Parempien satomahdollisuuksien toteutuminen edellyttää erityisiä sopeutumistoimia;

- Metsien kasvu ja tuottavuus nousevat. Ilmastonmuutos ja asianmukainen metsänhoito voisivat lisätä Suomen metsien sitomaa hiiltä jopa kolmanneksen. Kasvuolosuhteet ovat suosiollisemmat, erityisesti lehtipuille. Hyönteisten aiheuttamien metsävaurioiden odotetaan kuitenkin leviävän kauemmas pohjoiseen. Lämpimän sään jaksot talvella voivat saada aikaan epäsuotuisia fysiologisia vaikutuksia. Puunkorjuu vaikeutuu. Metsäpalojen riskin odotetaan kasvavan vuosisadan loppuun mennessä, erityisesti Etelä-Suomessa.

- Vuoteen 2020 mennessä pohjoisen merireitin vuotuisten liikennemäärien odotetaan kasvavan 1,5 tonnista 40 tonniin. Suuremmat liikennemäärät laskevat liikennöintimaksuja, jotka ovat tällä hetkellä suhteellisen korkeita pohjoisella merireitillä.

Globaali muutos alueilla, joilla ilmastonmuutoksen kielteiset vaikutukset tulevat selvästi näkyviin, voi johtaa sosiaalisiin ja taloudellisiin ongelmiin. Nämä liittyvät hallitsemattomaan muuttoliikkeeseen, ympäristön köyhtymiseen ja energian ja raaka-aineiden tuotannon laskuun, millä on taloudellista merkitystä myös Suomelle.

Arktisen alueen tuleva sosioekonominen kehitys riippuu valtioiden noudattaman politiikan tehokkuudesta ja niistä ohjelmista, joilla hillitään ilmastonmuutoksen vaikutuksia ja sopeudutaan niihin. On hyvin todennäköistä, että nämä eroavat huomattavasti toisistaan Pohjoismaissa ja Venäjällä. Suomessa kestävän kehityksen politiikka ja ohjelmat ovat hyvin kehittyneitä ja niiden toteutuksessa on onnistuttu[1]. Tämä antaa aihetta olettaa, että ilmastonmuutos ei vaikuta merkittävästi maan yhteiskunnallis-taloudelliseen kehitykseen seuraavien kahden kolmen vuosikymmenen aikana. Ilmastoennusteisiin sisältyvä huomattava epävarmuus vaatii kuitenkin, että yhdenmukaistamisstrategioita tehostetaan edelleen, jotta epäjohdonmukaisiin ja usein ristiriitaisiin ilmastoskenaarioihin liittyvät riskit ja menetykset voidaan minimoida.

Ilmakehän hiilidioksidikuorman vähentämisen tulisi olla perusta kaikille ilmastopakotteen hillintään tähtääville mielekkäille toimille. Mutta vaikka CO2-päästöissä saataisiinkin aikaan pikaista ja merkittävää alenemista, arktisella alueella tapahtuva nopea sulaminen (IPCC:n

---

[1] Ilmastonmuutoksen kansallinen sopeutumisstrategia, 2005; Kansallinen kestävän kehityksen strategia, 2006; Suomen kehityspoliittinen ohjelma, 2007; Kansallinen ilmasto- ja energiastrategia, 2008; Kansallinen luonnonvarastrategia, 2009.

ennusteen mukaan) ei välttämättä hidastu, koska hiilidioksidi säilyy ilmakehässä pitkään. On kuitenkin myös ilmastopakotteeseen vaikuttavia tekijöitä, jotka ovat lyhytikäisempiä kuin CO2. Näitä ovat muun muassa musta hiili (epätäydellisestä palamisesta aiheutuvat hiukkaset eli noki), troposfäärin otsoni sekä metaani (CH4). Koska nämä yhdisteet säilyvät ilmakehässä lyhyemmän aikaa kuin hiilidioksidi, niiden pitoisuuksissa aikaansaatu pieneneminen tuntuu paljon nopeammin kuin pitkäikäisten kasvihuonekaasujen päästöjen vähentäminen.

Mustan hiilen vähenemisen vaikutukset ovat voimakkaampia arktisella alueella kuin missään muualla, koska lumen ja jään suuri albedo lisää säteilyn heijastumista, jota mustan hiilen laskeumat puolestaan taas vähentävät. Kun tarkastellaan ainoastaan Eurooppaa, arktisen alueen ilmansaastetasoihin vaikuttavat eniten Euroopan pohjoisimpien maiden päästöt: ensimmäisenä tulee Norja ja sen jälkeen Suomi ja Ruotsi. Mustan hiilen päästöjen vähentäminen voi olla keino hidastaa arktisen alueen lämpenemistä, lyhentää sulamiskautta ja rajoittaa palauteilmiöitä.

Suurin osa arktiselle alueelle kulkeutuvasta mustasta hiilestä on peräisin dieselpolttoaineista, avotulesta (peltojen kulotuksesta ja metsäpaloista) ja kotitalouksien käyttämistä kiinteistä polttoaineista (mm. biomassasta). Öljyn ja kaasun etsintä pohjoisilla leveysasteilla on myös mahdollinen suuri päästölähde (tosin määrältään vielä huonosti tunnettu).

Suomessa suurimpia mustan hiilen päästölähteitä ovat kuljetukset (maanteillä ja maastossa) ja kotitaloudet (lähinnä puun poltto). Missään nykyisin voimassa olevista laeista ei keskitytä erityisesti mustan hiilen vähentämiseen, vaikka sen vähentämistä onkin käsitelty monissa poliittisissa aloitteissa (Arktisessa neuvostossa, Euroopan talouskomissiossa, YK:n ympäristöohjelmassa). Koska mustan hiilen päästöt kuitenkin tapahtuvat samassa yhteydessä kuin joidenkin muiden nykyisten lakien kattamien aineiden päästöt, on odotettavissa, että päästöjä saadaan vähennettyä monilla aloilla useimmissa arktisen alueen maissa, myös Suomessa.

Arktisen neuvoston kaikkien jäsenmaiden päästöjen vertailu osoittaa, että Suomen osuus arktiseen alueeseen vaikuttavista kokonaispäästöistä on vain muutama prosentti. Tämän vuoksi Suomi ei selvästikään pysty yksin saamaan aikaan merkittäviä vähennyksiä päästöissä tai säteilypakotteessa. Tarvitaan yhteisiä kansainvälisiä toimia, joita onkin parhaillaan käynnissä muun muassa Arktisen neuvoston piirissä. Eri maissa on erilainen päästörakenne, ja siksi yhteisessä päästövähennysstrategiassa on otettava nämä erot huomioon. Lisäksi kansainvälisen meriliikenteen aiheuttamat päästöt arktisella alueella voivat lisääntyä huomattavasti, jos jään sulamista koskevat ennusteet toteutuvat. Tämä puolestaan edellyttäisi, että kehitetään strategia rajoittamaan arktisen alueen laivaliikenteen päästöjä.

Venäjä on Suomen merkittävä kauppakumppani, jonka tärkeimmät vientituotteet Suomeen ovat energia, tietyt metallit ja raakapuu. Ennakoitu ilmastonmuutos Venäjän napa-alueilla ja havumetsävyöhykkeellä vaikuttaa ympäristöön ja vientiteollisuuteen eri tavoin. Ilmastonmuutos yleensä ja talvien lämpeneminen erityisesti helpottavat tuotantoprosesseja. Samanaikaisesti ikiroudan sulaminen hankaloittaa infrastruktuurin, erityisesti putkistojen ja teiden kehittämistä, lisää onnettomuuksia ja kasvattaa nykyisen infrastruktuurin ylläpitokustannuksia, mikä lopulta johtaa vientihintojen nousuun.

Venäjällä on merkittäviä yhteiskunnallis-taloudellisia ongelmia, jotka vaikeuttavat Venäjän arktisten alueiden kestävää kehitystä ja tätä myötä vahvistavat ilmastonmuutoksen kielteisiä seurauksia. Venäjän polttavimpia ongelmia ovat muun muassa: (1) lisääntyvä jälkeenjääneisyys pohjoisten alueiden yhteiskunnallis-taloudellisessa kehityksessä; (2) väestöpohjan supistuminen (korkea kuolleisuus, alhainen syntyvyys, muuttoliike, ikääntyminen jne.); (3) kuljetusjärjestelmien vanhentuneisuus; (4) uuden kilpailukykyisen ja ekologisesti puhtaan teollisuustekniikan puute; (5) mineraalivarojen etsinnän supistuminen; (6) alkuperäiskansojen perinteisen elinkeinojen häviäminen ja (7) alueella tuotetun tiedon ja tieteellisen osaamisen huomattava väheneminen.

Ilmastonmuutos vahvistaa näitä kielteisiä kehityssuuntauksia, ellei arktisten alueiden kansallista politiikkaa muokata välittömästi. Venäjän hallituksen viimeaikaiset päätökset viittaavat siihen, että Venäjä aikoo käydä käsiksi arktisten alueidensa kiireellisimpiin infrastruktuuria koskeviin ongelmiin. Tämän onnistuminen edellyttää kuitenkin merkittäviä sijoituksia ja huomattavaa kansainvälistä panosta.

Oletettavissa on, että venäläisen puun kysyntä ei laske merkittävästi Suomessa seuraavien kahden kolmen vuosikymmenen aikana. Ilmastonmuutoksen vaikutukset Venäjän metsiin ovat erilaisia Luoteis-Venäjällä (josta suurin osa Suomen nykyisestä ja tulevasta tuonnista on peräisin) ja Aasian puoleisella havumetsävyöhykkeellä. Kummallakin alueella on valtavat metsävarat. Euroopan puoleisilla pohjoisilla alueilla ilmastonmuutoksen odotetaan olevan keskimäärin samanlainen kuin Itämeren maissa. Alueen metsäteollisuuden suurimpia ongelmia ovat tehokkaan metsänhoidon puute, erittäin heikko infrastruktuuri ja vanhentunut konekanta ja tekniikka. Näin ollen metsäsektorin tuleva kehitys ja vientimahdollisuudet riippuvat pitkälti Venäjän tulevasta talous- ja yhteiskuntapolitiikasta, joissa edistys on edelleen hidasta. Ilmastonmuutoksen vaikutukset Siperian metsiin ovat rajumpia. Vakavat luonnon vaaratekijät, ennen kaikkea metsäpalot ja hyönteisten joukkoesiintymiset, muodostavat todellisen uhan metsien hyvinvoinnille. Infrastruktuurin ongelmat ovat akuutimpia Siperiassa kuin Euroopan puolella pohjoisessa. Jäämeren laivareitin avaaminen mahdollistaisi kuitenkin arvokkaan kuljetusväylän Siperian ”varaston” tarjoamille monille eri tuotteille Pohjois-Eurooppaan. Arktisen alueen laivareitteihin kohdistuu myös haasteita, jotka voivat tehdä liikenteen harjoittamisen kannattamattomaksi. Näitä ovat muun muassa korkeat vakuutusmaksut, infrastruktuurin puute, ankarat olot, ajojään ja jäävuorien aiheuttamat ongelmat sekä joidenkin väylien mataluus. Arktisen alueen meriliikenteen tulevalla kehityksellä on myös muita esteitä, jotka liittyvät erityisesti hallintoon ja infrastruktuuriin. Ratkaistavia kysymyksiä ovat arktisten laivareittien laillinen asema, sitovien ja yhtenäisten laivanrakennusstandardien puute, rajalliset radio- ja satelliittiyhteydet alueella ja avoimet kysymykset jotka koskevat alusten liikkeiden seurantaa ja valvontaa arktisella alueella. Tuleva globaali yhteiskunnallis-taloudellinen epävarmuus on merkittävä tekijä, joka määrittää energiakaupan geopolitiikkaa varsinkin Venäjän kaltaisen huomattavan energianviejän osalta. Nykyiset arviot epätavanomaisista ja uusista energiavaroista (muun muassa vasta löydetyistä arktisen alueen öljystä ja kaasusta) osoittavat, että ei niinkään energiavarojen rajallisuus, vaan taloudellista hyödynnettävyyttä ja ympäristöä koskevat kysymykset saavat energiantuojia (kuten Suomea) harkitsemaan siirtymistä muihin energianlähteisiin. Fossiilisten polttoaineiden hinnat todennäköisesti nousevat energian kysynnän kasvaessa ja edullisten fossiilisten polttoaineiden varantojen vähitellen ehtyessä, erityisesti kun otetaan huomioon yhä tiukemmat ilmastovaatimukset. Fossiilisten polttoaineiden nykyiset vaihtoehdot ovat kalliita, ja niin kauan kuin ei ole olemassa teknisiä innovaatioita, jotka alentaisivat niiden kustannuksia, vaikutukset Venäjän kaltaisiin energianviejiin pysyvät vähäisinä.

Jotta ilmaston tila saataisiin vakaaksi, hiilen käytön tulisi vähentyä nopeasti ja olisi otettava käyttöön useita kaasuja ja useita sektoreita (mukaan lukien maa- ja metsätalous) kattava strategia, jonka puitteissa toteutettaisiin monia erilaisia vähäpäästöisiä tekniikoita. Näitä ovat mm. negatiivisiin päästöihin johtavat tekniikat (esim. metsien hiilinielut ja hiiltä sitova biomassa). Ydinvoiman ja uusiutuvien energialähteiden katsotaan olevan tärkeitä tulevia keinoja tällä alueella ilmastonmuutoksen hillitsemiseksi. Tämä osoittaa, että nykyiset kansalliset politiikat Suomen kaltaisissa maissa voivat olla yhteensopivia vähäpäästöisen tulevaisuuden kanssa.

Ilmastopolitiikan toteutus voi saada aikaan perustavia muutoksia maa- ja metsätalouden taloudellisissa rakenteissa. Erityisesti tämä koskee uusien markkinoiden ja liiketoimintamahdollisuuksien luomista niiden lisätuottojen avulla, joita metsänistutus ja bioenergiaan liittyvä toiminta synnyttävät näillä aloilla. Ilmastonmuutosta hillitsevät politiikat, erityisesti tiukat kasvihuonekaasuja koskevat rajoitukset, voivat saada aikaan merkittäviä oheishyötyjä monien ilmansaasteiden, kuten mustan hiilen päästöjen kannalta, kun polttoaineissa ja tekniikoissa tapahtuu muutoksia. Tarvitaan kokonaisvaltaista politiikkaa, jonka avulla nämä mahdolliset edut voidaan saavuttaa täysimääräisesti.

1 EXECUTIVE SUMMARY

A growing interest in the Arctic by both coastal and non-coastal states has evolved over the last decades. According to some estimates, the Arctic hosts up to 90 billion barrels of oil and approximately one-third of unexplored natural gas resources. The coastal states (Canada, Denmark, Norway, Russia, and USA) have intensified attempts to extend their jurisdiction beyond the seabed outside of the exclusive economic zones that touch upon the interests of the three other countries of the Arctic Council (Finland, Iceland, and Sweden). There also is evidence of increasing interest in the Arctic by non-Arctic countries (e.g., the European Union, China). A primary objective for reducing negative anthropogenic impacts in the Arctic is improvements in the environmental management of the Arctic, specifically, preventing oil contamination in the Arctic Seas and adjoining lands, and combating transboundary air pollution, including stable organic pollutants. Special rules for the environmental protection of the Arctic have yet to be developed; the UN Convention on the Law of the Sea could, in this regard, serve as an overall framework.

Currently, the Arctic is at a cross-road in terms of its future development. We seem to have two options – either broad international cooperation aiming at the co-evolution of humans and nature, sustainable development of the fragile Arctic ecosystem, and improvement of the life standards of numerous indigenous groups or a new "Cold War" in the region – juridical conflicts and increasing disputes for control and military presence. Which path we choose will define the future fate of this very complex, vulnerable and dynamic region. Albeit it is unlikely that the Arctic will be completely demilitarized, the recent agreement between Russia and Norway on the maritime delimitation line, which now divides a long disputed area of the Arctic Ocean, is a step in the right direction toward finding an international solution for the exploration of the vast oil and gas deposits in the Barents Sea, and for the elaboration of a new treaty on international governance of the Arctic.

The impact of the climate on the Arctic plays a crucial role for Finland's, as well as other Nordic countries' current and future climatic conditions. Satellite observations reveal that the Arctic Sea ice extent has decreased since the end of the 1970s. The melting of ice in the Eurasian Arctic Seas is likely to open a shorter sea route between Europe, Asia, and the Pacific and to provide access to the Arctic's potentially vast seabed resources, including oil, gas, minerals, and fishery. The Arctic shipping lanes may also become more accessible to trade and tourism. However, a large number of challenges may limit the development of future shipping operations in the Arctic area. These include governance of the sea lanes, lack of key infrastructure in the area, and harmonized Arctic vessel standards. According to the Arctic Marine Shipping Assessment (AMSA) (Arctic Council, 2009), for example, most of the Arctic travel will continue to be destinational rather than trans-Arctic in 2020.

However, estimations on the future pace and extent of ice melt diverge considerably between the generally established view presented by the IPCC in its Fourth Assessment Report and that of independent research groups in Russia and elsewhere. The IPCC projections indicate that the ice melt will continue throughout the 21st century, and late summer sea ice is expected to virtually disappear completely toward the end of the projection period. However, alternative forecasts (e.g., that of the Russian Arctic and Antarctic Institute) predict a continuation (not trend) of the oscillatory character of the dynamics of the Arctic Sea ice area, attributable primarily to the regional specifics of climate cycles and long-period trends.

Regardless of which forecasts prove correct, in the coming decades sea ice will be present for much of the year and therefore access to the Arctic, such as the Northwest Passage and Northern Sea Route, will continue to be controlled by ice conditions in the future.

The thawing of permafrost in the vast areas of Northern Eurasia could lead to a rapid increase in carbon emissions (particularly in the form of methane). This feedback could significantly accelerate warming in the Arctic and affect the Earth's climate machine, resulting in additional emissions that are equal or greater than the current emissions attributable to deforestation in the tropics. Furthermore, the duration of the soil frost period will shorten toward the end of the 21st century. In central and northern Finland, the maximum annual soil frost depth will decrease, which may reduce but not eliminate the need to protect buildings and constructions, thus saving costs in the construction and transport sectors. On the other hand, reductions in soil frost could have negative impacts on the forestry sector, since harvesting becomes more difficult.

The northern territories of the Eurasian continent and adjoining seas (particularly the western regions) are expected to experience considerable warming and an increase in precipitation throughout the 21st century. Yet climate change will affect these regions both positively and negatively. The direct impacts may, *inter alia*, include:

- Negative impacts for and even threats to the existence of numerous biological species (polar bears, seals, walruses, northern deer and sea birds);
- An increase in the number and severity of large forest fires and pandemic insect outbreaks, particularly in the eastern continental regions of Northern Asia;
- The increasing variability of the climate will affect the vitality and productivity of terrestrial ecosystems. Summer droughts and winter thaws will have visible negative impacts on ecosystems. Warming will affect the heating regimes of lakes and the quality of the environment under the ice, which will likely decrease the productivity of aquatic ecosystems;
- Marine ecosystems are also quite vulnerable. A rise in temperature and decrease in ice cover will result in a northward shift of the boundaries of distribution of different fish species. Climatic change may lead to an expansion of exotic species, the acceleration of competition, increasing eutrophication and contamination. More favorable conditions are expected for some regions of the Arctic, which will bring a rise in the productivity of forage reserves, expansion of the area of population of certain fish species, intensification of fishing, and the migration of valuable commercial species;
- The reduction of the ice cover will improve access to the Arctic shelves. However, the predicted climate change in the Arctic will not decrease dangerous hydro-meteorological impacts, but instead redistribute these (an increase in the probability of high wind waves, movement of drift ice in new regions, etc.);
- It is very likely that the number and severity of dangerous climatic events will increase (strong winds, snowstorms, ice conditions of roads, decreasing ice conditions in seas, etc.);
- The impacts on the Arctic coastal area throughout the 21st century will include an acceleration in sea level rise (by 0.18—0.59 m, (IPCC 2007)), further increase in sea surface temperature, more extreme weather events and storm surges, altered precipitation and ocean acidification;

- Impacts will affect tourism, conditions for life and the health of the population, particularly the residents of high latitudes;
- Demand for heating may decrease and be to some extent replaced by the demand for cooling. Increased climate variability will encumber the achievement of long-term strategies based on the overall warming trend and the potential benefits these could bring.

On the whole, the expected climate change will have more favorable effects on the territories of the Nordic countries (particularly Finland) than on other regions of Northern Eurasia. These may, *inter alia*, include:

- The increase in annual precipitation will benefit hydro-power production. However, more frequent and dangerous floods and, in general, higher water flow is expected, which will affect civil engineering constructions;
- Climate change will open new opportunities for Finnish agriculture. A warmer climate will extend the thermal growing season and rate of physiological processes. This will allow for a substantial expansion of cultivable areas to include commonly grown major and minor crops, as well as for an increase in the yield of major field crops. The cultivation of new species will also become possible. The realization of high yield potential will require special adaptation measures;
- The growth and productivity of forests will accelerate. Climate change and proper forest management could increase the amount of carbon in Finnish forests by up to one-third. The growing conditions will be more favorable, particularly for deciduous trees. However, forest damage caused by insects is expected to spread further northward. Winter heat spells may prompt unfavorable physiological effects. Timber felling conditions will become more hazardous. The forest fire potential is expected to increase by the end of this century, especially in southern Finland.
- By 2020, the traffic volumes on the Northern Sea Route (NSR) are expected to increase from 1.5 to 40 million tons per year. The higher traffic volumes will lower the operating charges, which at present are relatively high on the NSR.

A number of social and economic problems may evolve from global change in other parts of the world, where the negative impacts of climate change will become clearly visible. These relate to uncontrolled emigration, impoverishment of the environment and a decrease in the production of energy resources and raw materials, which are also of economic significance for Finland.

Future socioeconomic developments in the Arctic region will depend on the effectiveness of state policies and on adaptation and mitigation programs. It is very likely that these will differ considerably in the Nordic countries and Russia. In Finland, sustainable development policies and programs are well developed and successfully being implemented[1]. This allows for the assumption that the country's socioeconomic development will not be significantly impacted by climate change over the next two to three decades. However, considerable uncertainty in climatic predictions requires further intensification of harmonization strategies in order to minimize the risks and losses related to inconsistent and often contradictory climatic scenarios.

---

[1] National Strategy for Adaptation to Climate Change, 2005; National Strategy for Sustainable Development, 2006; Finland's Development Policy Program, 2007; A National Climate and Energy Strategy, 2008; National Resources Strategy, 2009.

Reductions in the atmospheric burden of CO_2 should form the basis of any meaningful effort to mitigate climate forcing. Yet even if swift and profound reductions of CO_2 are made, the rapid melting in the Arctic (as projected by the IPCC) will not necessarily be delayed, owing to the long lifetime of CO_2 in the atmosphere. However, shorter-lived climate forcing agents (SLCF) than CO_2 exist, including black carbon aerosol (BC, a solid particle emitted from incomplete combustion, commonly known as "soot"), tropospheric ozone, and methane (CH_4). Due to a shorter residence time in the atmosphere than CO_2, reductions in the concentrations of SLCF's would be felt much sooner than a decrease in long-lived greenhouse gases.

The implications of BC reduction are stronger in the Arctic than elsewhere, because atmospheric absorption is enhanced by the high albedo of snow and ice surfaces, which, in turn, are reduced by BC deposition. When considering Europe only, Arctic pollution levels are most sensitive to emissions from the northern-most European countries, with Norway ranking first, followed by Finland and Sweden. Reducing BC emissions may provide a means to slow down Arctic warming, to curb the length of the melting season, and limit the feedback effects.

The use of diesel fuel, open burning (both agricultural burning and wildfires), and residential combustion of solid fuels (including biomass) account for the majority of BC that reaches the Arctic. Potentially large amounts of emissions (yet poorly quantified to date) result from the exploration of oil and gas in the northern latitudes.

The sectors in Finland with the highest BC emission intensities include the transport sector (road and off-road) and domestic combustion (primarily wood burning). None of the existing laws specifically targets the reduction of BC, although its reduction has been considered by a number of policy initiatives (Arctic Council, UNECE, UNEP). However, since BC is co-emitted with pollutants that are controlled by current legislation, a reduction in emissions by a number of sectors is expected in most of the Arctic countries, including Finland.

A comparison of emissions from all Arctic Council nations reveals that Finland only contributes a few percent of total emissions that impact the Arctic, and can therefore obviously not bring about marked reductions in emissions or forcing on its own. Consolidated international action, e.g., ongoing activities under the umbrella of the Arctic Council, is therefore necessary. The national emission structure varies from country to country and, consequently, a consolidated abatement strategy will have to take these differences into account. Finally, the rate of emissions into the Arctic by international shipping could significantly increase, should the ice melting scenarios materialize. This, in turn, would necessitate the development of a strategy to limit such emissions from Arctic shipping.

Russia is a major trading partner of Finland for energy sources, certain metals, and round wood. The expected climate change in the Russian polar and boreal regions will impact the environment and production of exported industrial goods in different ways. Climate change in general, and winter warming in particular, will facilitate production processes. However, the thawing of permafrost will, *inter alia*, complicate the development of infrastructure, specifically of product pipelines and roads, and increase the frequency of accidents and the maintenance costs for existing infrastructure, and finally, raise the price of exports.

Russia faces a number of substantial socioeconomic problems which hamper the sustainable development of the Russian Arctic and thus reinforces the negative consequences of climate change. Russia's most pressing problems, *inter alia*, include: (1) increasing lag in the socioeconomic development of its northern regions; (2) demographic decline (high death rate, low birth rate, emigration of population, ageing, etc.); (3) obsolescence of transport infrastructure; (4) lack of new competitive and ecologically clean industrial technologies; (5) decrease in the exploration of minerals stocks; (6) decline in the traditional economies of indigenous nations; and (7) substantial deterioration in the generation of information and scientific knowledge in the region. Climate change will aggravate these negative trends if the national policy in the Arctic is not immediately modified. Recent decisions by the Russian Government indicate that Russia plans to tackle the most urgent infrastructure problems in the Russian Arctic. However, in order to do so successfully, major investments and substantial international involvement will be necessary.

It is assumed that demand in Finland for Russian wood will not substantially decrease over the next two to three decades. The impacts of climate change on Russian forests will differ in North-West Russia (where the majority of current and future wood exports to Finland originate from) and in the Asian boreal region. Both of these regions have vast forest resources. On average, the climate change in the European North is expected to be similar to that in the Baltic countries. The major problems faced by the forest industry in this region include the lack of intensive forest management, the extremely weak infrastructure, and the obsolete machinery and technologies. Thus, future developments in the forest sector and its export potential will largely depend on Russia's future economic and social policies, which continue to lag behind. The climate change impacts on Siberian forests are more dramatic. Severe natural disturbance events, particularly fire and insect outbreaks, pose a real threat to the forests' survival. The infrastructure problem is more acute in Siberia than in the European North. However, the opening of the Arctic Sea route would establish a valuable transport passage to Northern Europe for the many diverse goods Siberia's "storage room" has to offer. The challenges that could make the utilization of Arctic shipping lanes unfeasible include, e.g., high insurance premiums, lack of infrastructure, harsh conditions, problems with drift ice and icebergs, as well as the shallow depths of some of the passages. The development of future Arctic maritime operations faces a number of additional obstacles related, in particular, to issues of governance and infrastructure. These include questions about the legal status of Arctic shipping lanes, the lack of binding and harmonized polar vessel construction standards, the limitations to radio and satellite coverage in the region, and open questions about the monitoring and controlling of the movements of ships in the Arctic.

Future global socioeconomic uncertainty will play a significant role in determining the geopolitics of energy trade, especially for major energy exporters like Russia. Current estimates on unconventional and new resources (including newly discovered Arctic oil and gas) indicate that concerns about economic recoverability and the environment are more likely to initiate a shift among energy importers (like Finland) to other sources of energy in the future than a severe limitation of resources.

Fossil fuel prices are likely to increase due to the rise in energy demand and the progressive depletion of low-cost fossil resources, especially in conjunction with ever-more stringent climate constraints. However, in the absence of technological innovations that can lower the costs of the currently expensive fossil fuel alternatives, the impacts on exporting economies like Russia will not be significant.

In order to achieve climate stabilization, the rate of decarbonization would have to increase rapidly and a multi-gas, multi-sector strategy (including agriculture and forestry) involving the implementation of a range of low GHG technologies, including negative emissions technologies (like forest sinks and biomass with carbon capture), would have to be implemented. Electricity from nuclear power and renewable resources are seen to play a major role in this region in the future in mitigating climate change, thus indicating that current national policies in countries like Finland can be compatible with low climate futures.

The implementation of climate policies could bring about fundamental changes in the economics of the agriculture and forestry sectors. This concerns, in particular, the establishment of new markets and business opportunities through additional revenues from afforestation and bioenergy activities within these sectors. Climate mitigation policies, especially stringent GHG reductions, can generate significant co-benefits for many air pollutants like BC emissions through shifts in fuels and technologies. This indicates the need for integrated policies that can fully realize these potential benefits.

2 INTRODUCTION

The objective of this review is to analyze "what is currently known about the effects of climate change and likely climate abatement policies on the accessibility and value of natural resources in Northern Europe in the Arctic Sea area, on the one hand, and on the logistical position of Northern Europe, on the other hand" with a special emphasis on Finland.

The Arctic is an enormous area around the North Pole that covers over one-sixth of the Earth's landmass. The Arctic region has a number of definitions. In this analysis, we mostly limit the definition to that part of the Arctic Ocean located across Northern Eurasia, to the high latitude territories (to approx. 50^{o} North) of the Northern Eurasian continent or to the Arctic nations including Canada, Denmark, Finland, Iceland, Norway, Sweden, Russia, and the United States.

Far-reaching and multi-faceted changes are taking place in the Arctic, which have profound consequences for the region's economic and political significance in international relations. This is compounded by the lack of applicability of a clear and comprehensive legal regime in the region. The applicability of the United Nations Convention on the Law of the Sea is not clearly defined (see Box 1). The five Arctic littoral states (Russia, Canada, the United States, Norway, and Denmark) are now seeking to increase their sphere of commercial activity by roving through seabed surveys eager to stumble upon a clause that stipulates that a specific area of the Arctic geographically belongs to their continental shelf. Other countries like China and Japan are also showing real interest in the region. This, in turn, has already led to the emergence of competing claims over sovereignty and to increasing military presence. Two nuclear powers – the United States and the Russian Federation – converge on the Arctic with competing claims and activities.

Today, the region is already a host to many environmental problems, including radiation from nuclear fallout and other dangerous pollutants that affect the flora and fauna of the region, sea life, birds, marine mammals, and their habitats. The population of the Arctic, which includes over 30 different indigenous nations, is at the mercy of ongoing and expected changes which may be global in scope, but are local in their manifestation.

Recent climate change has also had substantial influence on the region's natural environment which, in turn, has triggered new environmental impacts around the world. The climate change that has taken place in the Eurasian Arctic during the last decades has been dramatic. The rate of warming in the Eurasian Arctic is nearly twice as high as that of global warming. Research suggests that further major changes in the Arctic's environment and ecosystem – including melting ice and thawing permafrost – are to be expected. It is very likely that these changes will bring with them a number of serious regional and global consequences.

The impact of these future changes in the Arctic region will be of particular significance for countries like Finland. According to the IPCC and other national assessments, Finland will – depending on the respective emission scenario – experience a temperature increase of between 3 to 7 degrees, and a 13–30% increase in average annual precipitation. The temperature and precipitation changes are projected to be more pronounced during winter. Alternatively, the amount of mid-winter snow is expected to decrease by 30 to 60%. The occurrence of extreme weather events, e.g., heavy rain and subsequent floods, as well as heat waves will increase. Climate change will directly and indirectly affect the country's economy and human well-being. However, because we live in an increasingly interdependent world, Finland is largely dependent on its economic interactions with the rest of the world and, consequently, global change in other regions, particularly in Northern Eurasia, also affects Finland.

Although Finland does not have a coastline on the Arctic Ocean, the ongoing and expected climate change in the Arctic is likely to generate significant ramifications for the country's economy and population on account of:

- the region's high political profile and geopolitical position, which may lead to an acceleration of the race for energy rights and other natural resources of the Arctic, thus also increasing the likelihood of disputes over the rights of these resources, which may entail a number of security and military implications;
- the decreasing ice and warming temperature may unlock the Arctic seabed's natural resources and reveal new ones, in particular oil and gas deposits;
- the shrinking of the ice-cap and reduction in the area of sea ice may open new transport corridors in the Arctic Seas;
- the impacts of change in the Arctic on countries that have close economic relations with Finland (particularly Russia).

Given the considerable uncertainties of future climate change, it is important for all countries (in particular for Finland as a reputable global leader on climate change policy) to develop a long-term climate abatement policy that can mitigate some of the effects of climate change and hedge against some of its uncertainty. Developing robust energy systems in the face of uncertain climatic change will be crucial for an energy importing economy like Finland.

This report addresses some aspects of the problem, which is being researched at the International Institute for Applied System Analysis. The key issues dealt with in this report include:

1. An analysis of current and expected climate change in the Arctic with a special emphasis on Northern Eurasia. Coupled Atmosphere-Ocean Global Circulation Models (AOGCM), which IPCC forecasts are based on, indicate that severe warming will take place during the 21st century with catastrophic consequences for the Arctic ecosystem. However, these predictions are subject to considerable uncertainty, and AOGCMs do not necessarily reflect all regional and local details, particularly when it comes to such a distinctive region like the Arctic. To better elucidate this uncertainty, we have also included a discussion of studies that present an alternative point of view on the timing and probability of such climatic change;
2. Impacts of climate change on (1) transport availability in the Arctic, and (2) the production and delivery potentials of raw materials in Russia as one of Finland's major trading partners;
3. Climate abatement policies in the face of socioeconomic uncertainty and their potential impacts on the development of future energy systems;

4. Short-lived climate forcers, particularly black carbon, and their role in supplementing the activities to control CO_2 and other greenhouse gases in order to slow down Arctic warming. Within this context, we will also discuss Finland's current and future black carbon emission rate.

Box 1 The International Legal and Political Framework for the Arctic (adapted from Jakobson, 2010)

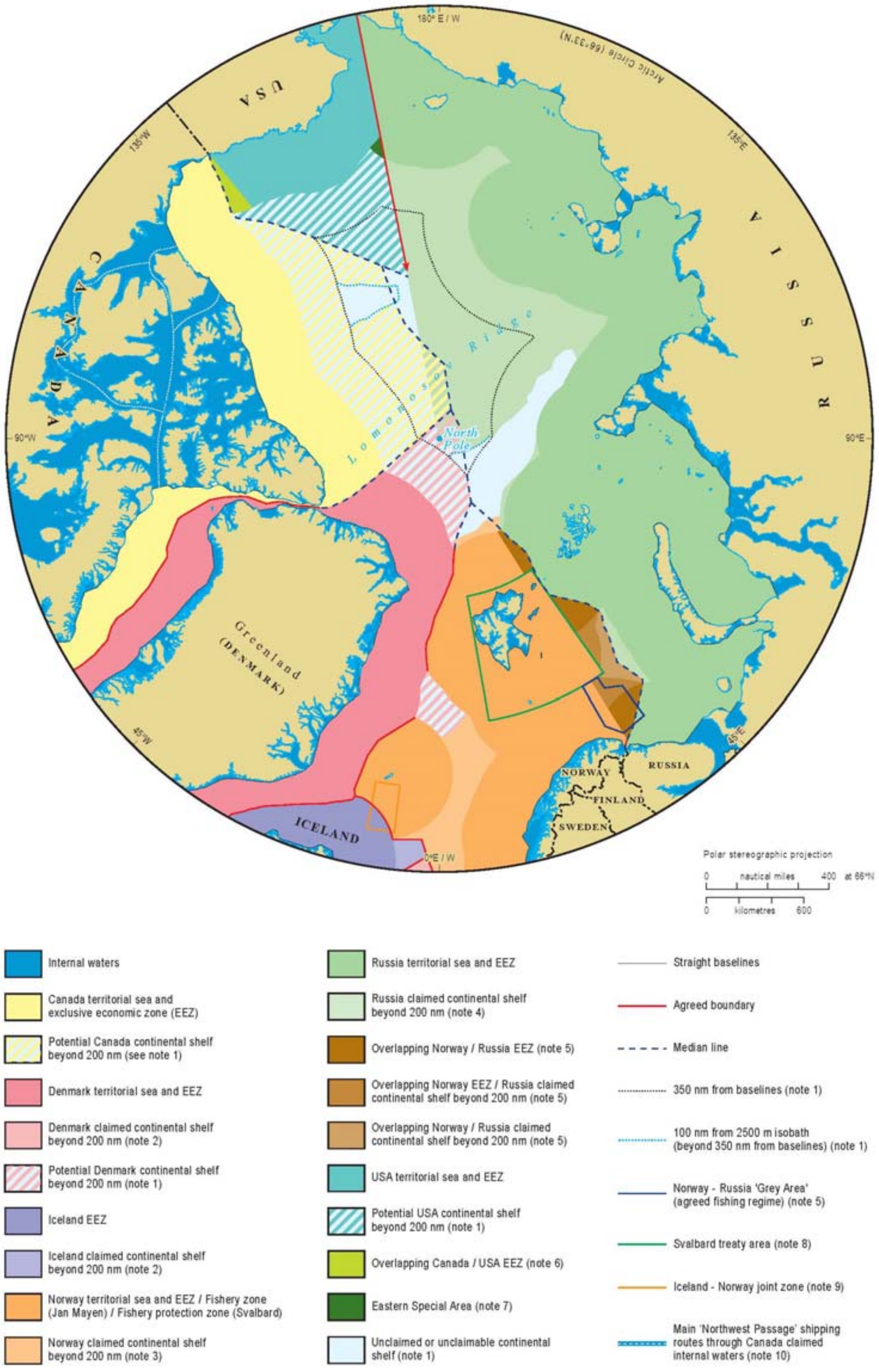
United Nations Convention on the Law of the Sea (UNCLOS)
Opened for signature at Montego Bay, Jamaica, on 10 December 1982; entered into force on 16 November 1994; 160 parties as of 1 January 2010; depositary UN Secretary-General. The Convention aims to regulate all aspects of the resources of the sea and uses of the ocean. According to UNCLOS, coastal (littoral) states have undisputed sovereign rights to their territorial sea and exclusive economic zone, which extends to a distance of 200 nautical miles (370 kilometers) from their coastal baseline (Articles 3 and 57). Finland is not a littoral state of the Arctic Ocean. *Treaty text*: *United Nations Treaty Series*, Vol. 1833 (1994)

The Arctic Council
Established by the Declaration on the Establishment of the Arctic Council (Ottawa Declaration), 19 September 1996; inaugurated 17 September 1998; 8 member states, 6 non-Arctic observer states and 3 ad hoc non-Arctic observer states. The Arctic Council is an intergovernmental forum that aims to promote cooperation among the Arctic states, in particular on issues of sustainable development and environmental protection. It is not an international organization with a solid legal charter, but rather an international forum designed to foster cooperation and collaboration on Arctic issues. Only Arctic Council member states have voting rights*. Website*: http://arctic-council.org/

International Maritime Organization Guidelines for Ships Operating in Arctic Ice-Covered Waters
Approved October and December 2002; issued 23 December 2002. The International Maritime Organization (IMO) Guidelines focus on the special climatic conditions of the Arctic and aim to promote the safety of navigation and prevention of pollution from shipping operations in the Arctic. The Guidelines are not legally binding. *Text*: International Maritime Organization, MSC/Circ.1056 and MEPC/Circ.399, 23 December 2002, http://www.imo.org/safety/mainframe.asp?topic_id=1787

Treaty concerning the Archipelago of Spitsbergen (Svalbard Treaty)
Signed by the 9 original parties at Paris, France, on 9 February 1920; entered into force on 14 August 1925; 40 parties as of 1 January 2010; depositary French Government. The treaty establishes Norway's full sovereignty over the Svalbard archipelago, but stipulates that it must remain demilitarized. Citizens from all states which are party to the Treaty enjoy equal right of access to and residence rights in Svalbard. *Treaty text*: *League of Nations Treaty Series*, Vol. 2 (1920).

Figure (introduction). Maritime jurisdiction and boundaries in the Arctic region.



Source: International Boundaries Research Unit, 2008.

3 ONGOING AND ANTICIPATED CLIMATE CHANGE IN THE EURASIAN ARCTIC

3.1 Observations of past and ongoing climate change

The climate of the Arctic has undergone rapid and dramatic change (IPCC, 2007, ACIA, 2005). Past climate change is characterized by regular and longer climatic cycles on decade-to-century time scales and was most likely caused by oceanic and atmospheric variability and variations in solar intensity. In the 1940s, the Arctic experienced a warming period. Nonetheless, the IPCC asserts that most of the global warming observed over the last decades is attributable to human activities (IPCC, 2007).

A distinct feature of climatic change in North Eurasia during the second half of the 20th century was the significant increase in temperature: The estimated warming trend is above 0.2 °C/10 years and up to 0.5°C /10 years in some "hot spot" regions of the continent; these hot spots are mostly found in eastern Siberia. The process is spatially heterogeneous: Maximal warming takes place in continental regions, and to a lesser extent in the maritime regions of the Arctic coast (Gavrilova, 2007; Onuchin & Burenina, 2008). The average warming in high latitudes was 1.5-fold higher than in southern Siberia and 3-fold higher than in Mongolia. The rate of warming is highest in central Siberia: Over the last century, the winter temperature increased by 10 °C in Jakutia, 7 °C in Pribaikalie, and 5 °C in Mongolia, with an increase in the annual average temperature of 2 to 3.5 °C. The growth period throughout the region (with a daily temperature of > 5 °C) increased by 1 to 2 weeks, more so in the south than in the north, and less so in more humid than in dry climates. The intensity of warming since the 1970s is 1.5 to 2 times higher as compared with that of the first half of the 20th century (Table 1).

Table 1 Linear trend in temperature (°C/100 year) for the Northern Eurasia regions (1976–2002).

Region	Year	Winter	Spring	Summer	Autumn
Western Siberia	3.7	6.8	8.5	1.2	-1.3
Central Siberia	5.3	7.3	7.7	5.9	0.5
Baikal Region	6.3	8.3	9.5	7.5	0.2
North-East of Asian Russia	4.4	-0.8	8.2	4.4	5.5
Russian Federation	4.9	6.7	7.1	4.6	1.6

Source: Gruza et al., 2002.

Observations of Arctic precipitation are restricted to a limited network of stations and are often unreliable since winter snowfall cannot be accurately measured due to drifting snow. On the whole, trends in annual and seasonal precipitation differed by season: A positive precipitation trend was observed in winter (2 to 5 mm/10 years) and a negative one in summer (2 to -7 mm/10 years). The annual amount of precipitation in northern Europe and western Siberia has increased significantly. A tendency toward a decrease in precipitation was observed in continental regions of central and eastern Siberia (e.g., -4.1mm/100 years for the area around the Lake Baikal). The increasing aridity of the climate is characteristic of practically all of continental northern Asia.

One of the integral climatic indicators often used to identify possible water stress in plants (or lack thereof) is the Palmer Drought Severity Index (PDSI) (Palmer, 1965). Negative PDSI values signify prolonged drought, while values greater than zero reflect normal or wet spell conditions. An evaluation of empirical orthogonal functions of this index reveals that most changes since 1950 in the PDSI for Siberia can be explained by linear trends toward drier conditions. The index has increased toward wetter conditions in Scandinavia and northern European Russia (but only slightly in southern regions) (Dai et al., 2004, Lapenis et al., 2005).

Permafrost covers almost two-thirds (65.5%) of the northern Eurasian territory. Continuous permafrost occupies 40% of the territory, whereas discontinuous and island permafrost occupy 11.4 and 14.1% of the area, respectively (Melnikov & Pavlov, 2006). The high vulnerability of frozen quaternary deposits is attributable to their low temperature (up to -16 °C on the Arctic shoreline) and large ice content in the form of ice inclusions and ice below ground. Geothermic and cryogenic conditions have resulted in the development of dangerous cryogenic geologic processes and the destruction of infrastructure in high latitudes east of Finland.

An intrinsic feature of ongoing climate change is the high degree of regional heterogeneity of high latitude climate in two dimensions: The 100 year rate and cycling. Melnikov and Pavlov (2006) found that continental Russia in particular experienced a significant climate change (> 1 °C) in the 20th century, (1.4 to 2.1 °C for approximately 50% of its territory), while 1/5 and 1/3 of the territory experienced moderate (0.8 to 1.0 °C) and weak (<0.8 °C) climate change, respectively. The highest rate of climate change was evident south of Siberia (0.008 °C /year), the lowest rate was recorded in northern Europe and the plains of East Siberia (0.002 °C /year).

The growing season of high-latitude terrestrial ecosystems increased by 12 days during the years 1981–1991 (Myneni et al., 1997). A positive feedback between spring snow-cover disappearance and radiative balance can result in warmer spring air temperatures. This is likely to exacerbate the continued early thaw and onset of the growing season, resulting in further modifications in productivity and net C uptake (McGuire et al., 2001). Even minor changes in global temperatures could result in imbalanced responses in Arctic and boreal regions, with positive feedbacks that could enhance certain processes, such as photosynthesis and respiration.

Winter has become shorter by between 8–13 days (Romashova, 2004). Furthermore, warm winters occur 2–2.8 times more frequently than they used to. These trends have changed the relationship between heat and humidity, which defines the dynamics of important ecosystem processes and the functioning of natural systems. The recurrence of strong winds (>15 m sec^{-1}) has increased by 3–13 times in recent decades (Romashova, 2004). The increase in snow depth in some regions (e.g., in East Siberia) has shifted to the south. The runoff of large Siberian rivers has also increased. Despite the substantial spatial heterogeneity of climate change throughout the region, the increase in temperature in large parts of continental North Eurasia was not compensated for by the change in precipitation. It has lead to increased aridity of climates, particularly in the continental regions.

Observations and climate models indicate that present-day changes in radiation forcing affect surface heat, moisture budgets, and hydrological regimes of large territories. Permafrost and seasonally frozen ground have brought about significant changes in most regions (especially in high latitudes) in recent decades. Between the 1960s and 1990s, the permafrost temperature in East Siberia increased by approximately 1 °C at a depth of 1.6–3.2 m, and by 0.3 °C to 0.7 °C at a depth of 10 m in northwestern Siberia. Long-term monitoring of the depth of the active layer of permafrost reveals a statistically significant increase by approximately 21 cm between 1956 and 1990. The results of permafrost monitoring from 1989 to 2002 published by the Institute of Cryolitozone (Yakutsk) indicate that, under present-day warming trends, a rapid degradation of the upper part of ice-rich soils of both undisturbed and disturbed permafrost landscapes is taking place, with a 5–30% loss in ground ice, and a particularly severe degradation of disturbed sites (Gavriliev, 2003).

Some uncertainties of climate change predictions in the Arctic are generated by the sparse network of meteorological stations (currently, only about 80 meteorological stations that provide data on a relatively long period of observation work in the Russian high latitudes), which are predominantly located in plains and outside of forests.

3.2 Prediction of future climate

Climate change predictions are usually based on coupled atmospheric-ocean global circulation models (AOGCM). These models (derived from physical laws) provide a physically consistent picture of future climate change in contrast to all other available methods used to forecast future climate. The AOGCMs currently being used offer the maximum level of knowledge we have today on possible future climate change scenarios. At present, there are only few available alternatives to scientifically project climate change.

Several projections of the Arctic climate have been presented. ACIA (2005) used five different global climate models (CGCM2, Canadian Centre for Climate Modelling and Analysis; CSM_1.4, National Center for Atmospheric Research, United States; CHAM4/ OPYC3, Max Planck Institute for Meteorology, Germany; GFDL-R30_c, Geophysical Fluid Dynamics Laboratory, United States; and HadCM3, Hadley Centre for Climate Prediction and Research, United Kingdom) coupled with two different emissions (GHG and aerosol) scenarios (B2 and A2). Other assessments are based on HadCM3, CSIRO, NCAR-PCM, ECHAM4, CGCM2, GFDL and CCSR NIES by large regions (of which four cover the Northern Hemisphere's Arctic and boreal regions within the framework of the IPCC Scenarios A1F1 (fossil intensive), A2, B2, B1, in descending order, of radiative forcing by 2100). The divergence between the projection results of the individual models is quite high (Table 2) -temperature and precipitation deviate by a factor of 10 (the maximum increase in temperature lies at 16–18 °C during certain periods according to the CCSR NIES model and precipitation could increase by up to 100% according to the ECHAM4 model).

Table 2 Projection of changes in temperature and precipitation in high latitudes for the 21st century based on different AOGCMs.

Period	December-February		March-May		June-August		September-November	
	ΔT, oC	ΔP, %%	ΔT, oC	ΔP, %%	ΔT, oC	ΔP, %%	ΔT, oC	ΔP, %%
Arctic Land (67.5 S Lat, 90 N Lat)								
2010–2039	+1.6; +3.6	+4; +24	+1.3; +3.0	+2; +19	+0.7; +3.0	+3; +16	+2.1; +4.7	+2; +17
2040–2069	+2.7; +8.7	+6; +55	+2.1; +5.6	+7; +37	+0.9; +5.5	+6; +32	+2.6; +9.3	+5; +40
2970–2099	+5.0; +18	+9; +81	+3.0; +11	+10; +62	+1.0; +8.0	+5; +51	+3.8; +14	+9; +62
Northern Asia (50.0 S Lat, 67.5 N Lat, 40.0 W Lon, -170.0 E Lon)								
2010–2039	+0.9; +5.5	+3; +36	+0.7; +3.8	+3; +17	+0.7; +2.9	+1; +10	+1.0; +3.9	+3; +16
2040–2069	+1.8; +9.6	+7; +70	+1.2; +6.5	+9; +39	+1.1; +5.2	+1; +15	+1.9; +7.1	+5; +20
2970–2099	+3.0; +16	+9; +105	+2.0; +13	+10; +71	+1.6; +9.1	+3; +28	+2.1; +12	+9; +31
Northern Europe (47.5 S Lat, 67.5 N Lat, -0.10.0 W Lat, 40.0 E Lon)								
2010–2039	+1.0;+4.1	+2; +22	+1.0;+3.0	-2; +16	+0.6; +2.2	-5; +8	+0.9; +3.0	-4; +12
2040–2069	+1.8; +8.5	+1; +41	+1.0; +7.0	+1; +28	+1.0; +3.9	-10; +15	+1.7; +5.9	-1; +16
2070–2099	+2.2; 13.9	+6; +60	+1.8; 11.2	+5; +49	+1.2; +6.2	-21; +18	+1.9; +9.0	0; +21

Source: Ruosteenoja et al., 2003.

The divergence in the projections for each region is very high. However, some common trends emerge for all high latitude regions of North Eurasia, namely:

- by the end of the 21st century, an increase in average annual temperature by approx. 4 °C is anticipated for 60–90o NL, and by >5 °C for the central Arctic;
- the maximum increase in temperature is predicted mostly for cold months (December to February); the average increase by the end of the century is expected to be around 10 °C; maximal summer warming is limited to 1 °C for the major part of the Arctic;
- by 2100, a minimal increase in temperature by approx. 6 °C is expected for spring and summer (March to August);
- considerable increases in precipitation are expected; however, the projections differ considerably – precipitation over the Atlantic sector of the Arctic could increase by 5 to 10% between 2071–2090, and by up to 35% in other regions, mainly in the winter and fall, and a minimum increase is projected in the summer;
- an increase in precipitation is expected, primarily during winter;
- an increase in climate aridity is projected for the southern continental regions;
- an increase in river discharge by 11.1% on average is anticipated between 2071–2090, but only by 3.2% between 2011–2030;
- shrinking ice cover with a very high variability – e.g., between 9 and 16 million km^2 by the end of March (the average by the end of March at the close of the 20th century was approx. 14 million km^2);
- no definite conclusion on changes with regard to extreme events;
- Scenarios A2 and B2 only differ significantly after the 2050s.

Decreasing the precipitation in continental areas of the Asian high latitudes could turn out to be critical for terrestrial ecosystems. Table 3 presents projections of changes in temperature and precipitation based on 16 coupled AOGCMs, using the IPCC Scenario A2 for Asian Russia (Meleshko et al., 2008). The anticipated changes are compared to the base climate period of 1980–1999.

Table 3 Projection of changes in temperature and precipitation in the 21st century in Asian Russia, based on 16 coupled AOGCMs.

Region	2011–2030		2041–2060		2080–2099	
	Winter	Summer	Winter	Summer	Winter	Summer
Surface temperature (˚C)						
West Siberia	1.4±0.7	0.8±0.5	3.4±1.0	2.0±0.8	7.2±1.8	4.4±1.4
East Siberia	1.5±0.6	0.8±0.4	3.6±1.0	1.7±0.7	7.7±1.7	3.9±1.4
All of Russian territory	1.4±0.7	0.8±0.4	3.4±0.8	1.9±0.7	7.2±1.7	4.2±1.3
Precipitation (change in % to current climate)						
West Siberia	7±4	1±1	16±8	4±3	39±11	7±6
East Siberia	10±3	3±3	19±7	6±4	45±14	14±7
All of Russian territory	6±3	2±1	14±5	4±3	34±8	8±5

Source: Meleshko et al., 2008.

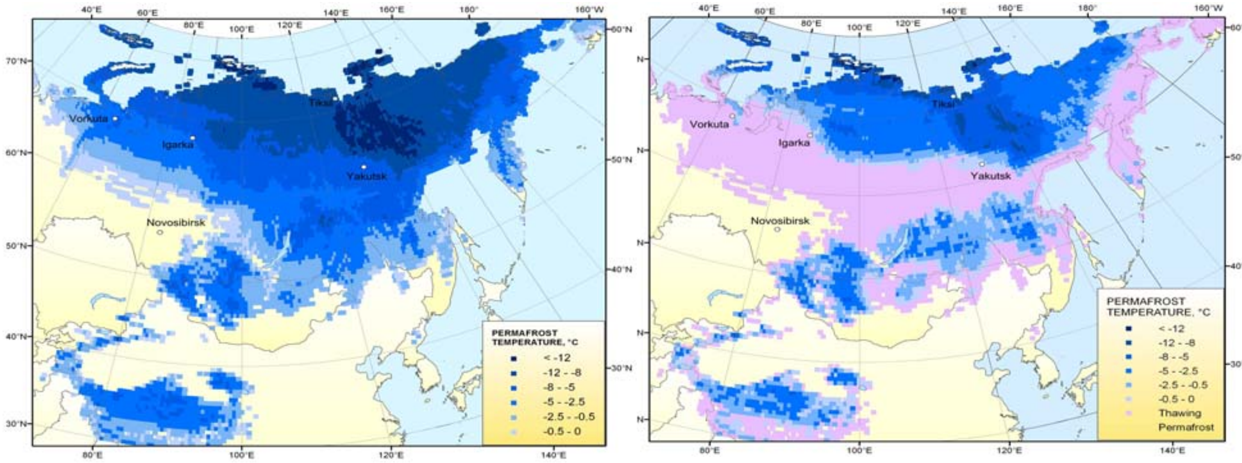
Modeling studies on permafrost behavior in the 21st century predict a decrease in the total area of permafrost by 10–18%, 15–30%, and 20–35% by 2030, 2050 and 2080, respectively (Anisimov et al., 2003). Widespread thermokarst development, gully formation, landslides, solifluction, floods, paludification (or aridity, depending on geographical distribution and landscape peculiarities) are expected for large areas, especially those with ice-rich soils (which cover approximately 35% of Yakutia and 35–40% of northeastern parts of Russia). According to projections by the Institute of Cryolitozone in Yakutsk, the number of lakes and swamps may increase (by 1.3–3 times, presuming a future moderate warming of +3 °C) at different rates in different regions of northern Asia. If the observed warming trend $\Delta t_0 \geq 0.06–0.09$ °C yr^{-1} continues, unprecedented changes in the geocryological and ecological conditions and landscape are very likely in high latitudes of North Eurasia (Ivanov & Maximov, 2003).

The warming will likely trigger an explosive rise in emissions of carbon stored in permafrost, wetlands and territories (a total amount of 500–700 Pg) (e.g., Desjatkin & Desjatkin, 2007). According to a study by Zimov et al. (2006), the total amount of carbon in the Siberian ground is estimated at around 1000 Pg C, including approx.500 Pg C in *yedoma* and 400 Pg C in non-*yedoma* permafrost, and 50 to 70 Pg C in the peatlands of West Siberia.

Recently, Khvorstyanov et al. (2008a, 2008b), using a new model within the SRES-A2 transient climate warming scenario of the IPSL CM4 climate model, found that the carbon-rich Pleistocene soil could emit 256 kg C m^{-2} into the atmosphere, including 20 kg C m^{-2} released as methane, from the East Siberia *yedoma* areas alone.

Changes in the intensity of river runoff and its seasonal redistribution are also evident (Shiklomanov & Georgievsky, 2007), a tendency that will accelerate during the 21st century (Meleshko et al., 2008).

Figure 1 Dynamics of permafrost (1980–2000 and 2080–2100).



Source: Romanovsky et al., 2001.

3.3 Permafrost and soil frost in Finland

Palsa mires are a feature of permafrost in Finland. Palsa mires are subarctic mire complexes with permanently frozen peat hummocks (Fronzek et al., 2009). They occur in high latitude environments in parts of Fennoscandia, Russia, Canada, and Alaska where they are a characteristic and unique feature of nature (Fronzek et al., 2009). According to Fronzek et al. (2009), Palsas are very sensitive to climatic conditions and have been decreasing throughout their distribution range in the Northern Hemisphere. This trend can be expected to continue with further changes in the climate. Palsas are one of the 65 priority natural habitat types listed in Annex I of the "Habitats" Directive of the European Union (Fronzek et al., 2009).

Climate change has induced changes in soil frost conditions. According to Venalainen et al. (2001a, 2001b), the duration of the soil frost period will shorten by the end of the century in all countries. In central and northern Finland, the maximum annual soil frost depth will decrease. Decreasing soil frost may reduce the needs for protecting buildings and constructions, which would save costs in the construction and transport sectors (Mattila et al., 2005). Reductions in soil frost may have negative consequences for the forestry sector, which implies that harvesting would become more difficult. Soil frost also protects the roots of trees from damages by harvesting machinery and improves the anchoring of trees in the ground, thus reducing storm damages (Ministry of Agriculture and Forestry of Finland, 2005). The decrease in snow cover in southern Finland increases the probability of frozen grounds in the middle of winter.

In any case, it seems that soil frost will continue to exist in all parts of Finland, despite climate change, but the significant annual variation in soil frost conditions will nonetheless result in the need for soil frost protection. The decreasing soil frost due to climate change may also have some negative effects for forestry.

3.4 Uncertainties of climate predictions

The question how realistic predictions of the future climate in the Arctic are, is quite significant: Profound uncertainties with reference to the observational data and climatic models exist (e.g., Kondratiev, 2004). As implied by ACIA (2005) and IPCC AR4, our understanding of the polar climate system continues to be incomplete due to (1) its complex interactions between and within the atmosphere-land-cryosphere-ocean-ecosystem, involving a variety of distinctive feedbacks; (2) several important systems features, which are not adequately represented in the models (clouds, boundary layer processes, sea ice, etc.); (3) the high variability of the climate on the annual and decadal time scale; (4) the diversity of natural atmospheric patterns like the NAM, the NAO, the PDO (Pacific Decadal Oscillation), etc., and (5) the inconsistency in the results of regional and global climatic models, the low resolution of global models, the scarce number of observations and limited knowledge of the developing processes in polar regions also contribute considerably to the high degree of uncertainty.

Many scientists and institutions assert that the recent climate change in polar regions has natural drivers (Gudkovich et al., 2003, Konratiev, 2004, Frolov, 2006). They argue that (1) despite the exponential increase in GHG concentration, no substantial increase in air temperature and reduction of ice cover was observed during the 20th century; (2) the change in air temperature and in the area of ice cover was cyclic during the 20th century (the most important cycle lasted 50–60 years and its impact on inter-annual dispersion makes up more than 30% of the change); (3) the current hydro-thermodynamic models do not account for these cycles, nor for past climate change; (4) some research claims that the decreasing thickness of Arctic ice is a dynamic, but not a thermo-dynamic phenomenon caused by anthropogenic warming (Gudkovich et al., 2002); (5) the verification of the models does not usually include natural cycling, and (6) the models used do not take account of climate carbon cycle-feedback (IPCC, 2007). Based on the recognized 60-year cycle, scientists of the Arctic and Antarctic Research Institute (St. Petersburg) predict that the conditions of the Arctic Seas by the middle of this century will be similar to those in the mid-1970s (thus decreasing the anomaly of the air temperature in the Arctic by -0.5 °C, increasing the ice cover area of the northern seas up to 1.2 M km2, as well as that of the seas of the Siberian Arctic shelf to 1.6 M km2 (Gudkovich et al., 2002). In order to present a complete picture, we have also included a short description of an alternative view of the future climate in the Arctic.

3.5 Arctic Sea Ice in a changing climate

Satellite observations reveal that the Arctic Sea ice extent has decreased since the end of the 1970s (IPCC, 2007). The melting of the Arctic Sea ice has raised increasing interest not only among the Arctic Council nations, but also among nations close or outside of the Arctic area (Jakobson, 2010). The melting of sea ice provides possibilities to, inter alia, exploit the Arctic's vast oil, gas, minerals, and fishery resources, and to utilize the Arctic shipping lanes more efficiently for trade and tourism (Jakobson, 2010). For example, the Northern Sea Route (or Arctic Sea Route) shortens the shipping routes between Asia and Europe by over 6000 km. The increased interest in the Arctic also brings with it some challenges to the region's economic, military, and environmental governance (Jakobson, 2010). However, significant uncertainties exist not only with regard to the estimates/measurements of the ice thickness and its extent, but even more so with regard to predictions on the future of the Arctic ice.

In this report, we present two perspectives, the well-known and fairly established view published by the IPCC in its Fourth Assessment Report (IPCC, 2007), and the view of the independent Russian research groups from the Arctic and Antarctic Research Institute (St. Petersburg) based on their research in the Arctic over the last decade.

The IPCC projections on the Arctic Sea ice extent indicate that the ice melt will continue throughout the 21st century, and that the late summer sea ice could disappear almost entirely toward the end of the projection period. However, Russian scientists have recently introduced a different Arctic ice scenario. They predict a continuation (not trend) of the oscillatory character of the dynamics of the Arctic Sea ice area attributable primarily to regional specificities of climate cycles and long period trends. They expect that the ice area will increase during the summer during the period 2020–2040, and will reach its peak sometime between 2030–2035 in the Eastern Seas and in 2035 in the Western Seas. The second peak is likely to occur around 2090–2095. The period of lower ice cover is expected in 2050–2070 and at the beginning of the 22nd century. This projection contradicts the conclusions IPCC AR4 arrives at, namely, that a dramatic shrinking and even disappearance of the ice cover along the ASR will begin as early as the 2050s.

Even if the most optimistic scenarios of the IPCC on Arctic melting turned out to be correct, there are challenges that could make the use of the Northern Sea Route and other Arctic shipping lanes unfeasible in the near future. Jakobson (2010) mentions high insurance premiums, lack of infrastructure, harsh conditions, problems with drift ice and icebergs, as well as shallow depths in some of the passages.

3.5.1 Arctic Sea ice extent according to the IPCC (2007)

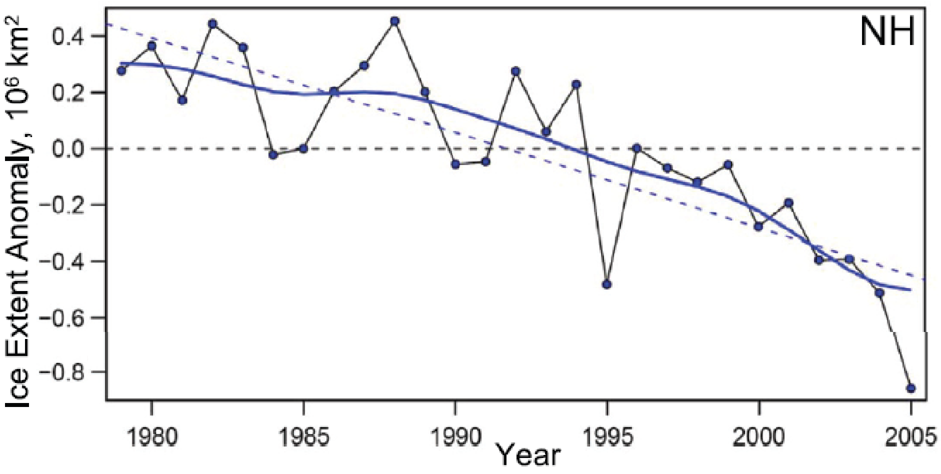
Sea ice plays an important role in the global climatic system, since it increases the albedo (reflectance) in high latitudes, modifies the exchange of heat, gases, and momentum between the atmosphere and oceans, and redistributes fresh water via transport and melt of sea ice (IPCC, 2007). Arctic Sea ice is especially sensitive to global warming. Late summer sea ice is projected to disappear almost completely toward the end of the 21st century. A number of positive feedbacks in the climate system will accelerate the melt back of sea ice: (1) The ice-albedo feedback allows open water to receive more heat from the sun during summer, and (2) warmer waters and stronger circulation further reduce the ice cover. Some climatically important characteristics of sea ice are its concentration, extent or edge position, total area and multi-year area, its velocity, thickness (closely connected with ice strength, which influences the navigability with ships), as well as its growth and melt rates (IPCC, 2007).

The melting of sea ice does not affect the sea level, since it already floats in the sea. This does not apply to the ice sheets that lie on top of land. The most important ice sheet masses worldwide are the Greenland and the Antarctic ice sheets, and changes in their mass balance have implications for the sea level. The IPCC maintains that the potential rise in sea level could reach between approximately 7 to 57 meters, if the Greenland or Antarctic ice sheet melts, respectively. The IPCC (2007) has determined that the Greenland ice sheet is currently undergoing inland thickening, faster near-coastal thinning and a recent acceleration in overall shrinkage. According to the IPCC (2007), the melting of the Greenland ice sheet is expected to continue.

Sea ice extent is the only ice variable for which observations are available over several decades. The measurement accuracy of the satellite radiometers is approximately 12 to 25 kilometers, depending on the instruments used. Recently launched instruments have improved accuracy and provide important additional data to previous observations, e.g., on the dynamics of the ice sheets. The CryoSat was recently launched and will provide necessary data to fill the current knowledge gaps (Schiermeier, 2010).

The IPCC (2007) presented a time series of the Arctic Sea ice extent from the end of the 1970s until 2005 based on satellite data. The Arctic Sea ice extent is experiencing a significant decreasing trend, whereas the Antarctic indicates a slightly positive trend (Fig. 2). The trends are stronger in the summer and weaker in winter. Figure 3 illustrates the trends of the sea ice extent in March and September from 1978 to 2009, as presented in AMAP (2009). The figures (Fig. 3 and 4) clearly show that a substantial interannual to decadal variability exists. In Figure 4, the Russian data indicate anomalously little ice during the 1940s and 1950s, whereas the Nordic Sea data denote an anomalously large ice extent at this time, emphasizing the importance of regional variability (IPCC, 2007).

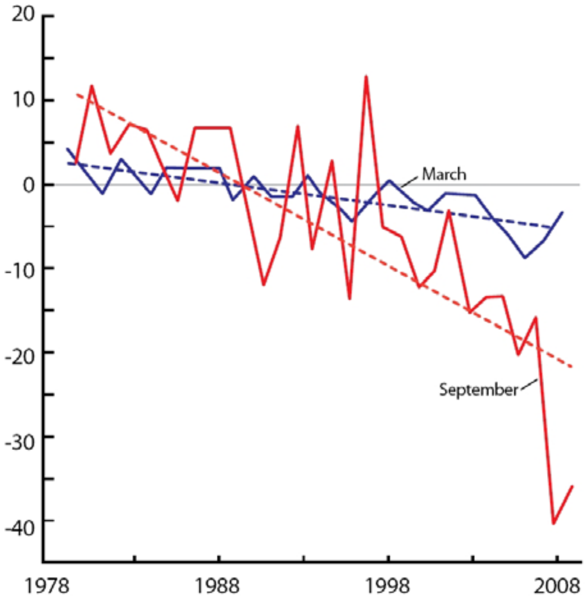
Figure 2 Sea ice extent anomalies relative to the mean of the entire period for the Northern Hemisphere, based on passive microwave satellite data.*



* Symbols indicate annual mean values, the smooth blue curves show decadal variations, and the dashed lines indicate linear trend lines.

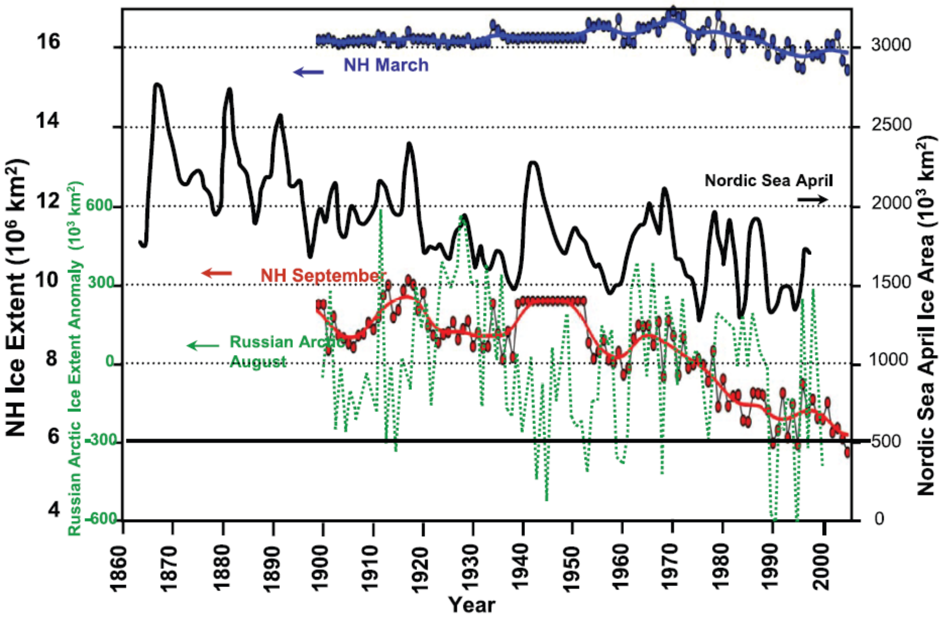
Source: IPCC, 2007.

Figure 3 Sea ice extent: Average percentage difference from 1979–2007.



Source: AMAP, 2009.

Figure 4 Long-term time series of the Northern Hemisphere (NH), Nordic Seas, and Russian Archipelago Sea ice extents based on several sources (see details in IPCC, 2007). For the NH time series, the symbols indicate annual values, while the curves signify the decadal variation.

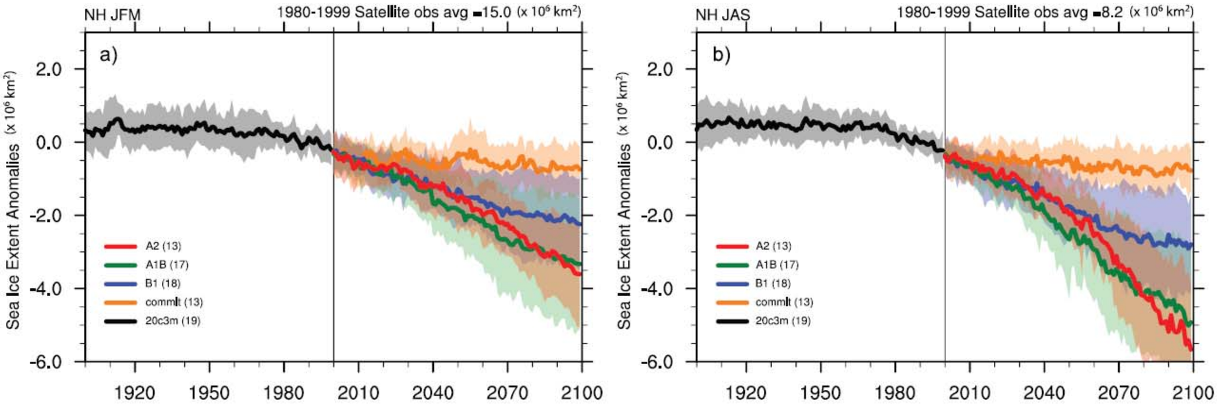


Source: IPCC, 2007.

3.5.2 Future projections of the Arctic Sea ice extent according to the IPCC (2007)

Atmospheric model results project future warming which is amplified at high latitudes (IPCC, 2007). The warming is most prevalent in autumn or early spring. The models reveal a range of possibilities in the Northern Hemisphere sea ice extent, from very little change to a severe and accelerated reduction during the 21st century, depending on the given scenario (Figure 5). The summer ice area is projected to decline more rapidly than that of the winter ice. Figure 6 illustrates the decrease of the Arctic Sea ice minimum extent in 1982 and 2007, and climate projections on a map based on satellite observations (National Snow and Ice Data Center, NSIDC) and ACIA (2004) models.

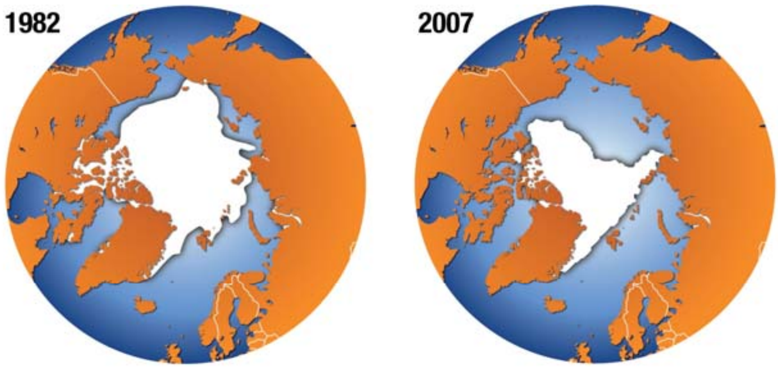
Figure 5 Multi-model simulated anomalies in the sea ice extent for the 20th (20c3m) and 21st century using the SRES A2, A1B, and B1, as well as the commitment scenario for (a) Northern Hemisphere from January to March (JFM), and (b) Northern Hemisphere from July to September (JAS).*



* The solid lines represent the multi-model mean, the shaded areas denote ±1 standard deviation. Sea ice extent is defined as the total area where sea ice concentration exceeds 15%. Anomalies are relative to the period 1980 to 2000. The number of models is provided in the legend and differs for each scenario.

Source: IPCC, 2007.

Figure 6 The decrease of the Arctic Sea ice minimum extent in 1982 and 2007 based on satellite data (NSIDC), and climate projections based on ACIA 2004 models.*



National Snow and Ice Data Center, 2007

Arctic Climate Impact Assessment, 2004

* Figure prepared by Hugo Ahlenius, UNEP/GRID-Arendal (http://maps.grida.no/go/graphic/the-decrease-of-arctic-sea-ice-minimum-extent-in-1982-and-2007-and-climate-projections)

3.6 Arctic shipping

According to the Arctic Marine Shipping Assessment (AMSA) (Arctic Council, 2009), natural resource development and regional trade are the key drivers of increased Arctic maritime activity, but a large number of challenges define the future and may limit the development of future maritime operations in the Arctic area. Key governance and infrastructure challenges for Arctic shipping are listed below based on key findings of AMSA (Arctic Council, 2009):

- There are still open questions and divergent national views about the legal status of the Arctic shipping lanes, e.g., which country has claims over the waters, etc. The legal status has consequences with regard to the extent to which a given coastal state can unilaterally impose construction, crewing, and equipment standards;
- Development of meteorological, oceanographical and ice information services, as well as the development of hydrographic services and charts (especially the Northwest Passage). Despite the longer navigation seasons, ice conditions will continue to present a challenge for maritime navigation in the Arctic in the future and due to climate variability, the ice situation will vary from year-to-year;

- Lack of binding and harmonized polar vessel construction standards. The IMO standards could, for example, be developed to achieve this aim. This also applies to cruising ships operating in the Arctic;
- Monitoring and controlling the movement of ships in the Arctic;
- Limitations to radio and satellite communication coverage;
- Lack of emergency response capacity;
- Availability of skilled mariners and ice navigators that are used for Arctic conditions. There are no requirements for education, training and/or certification of Arctic mariners and navigators;
- The availability and costs of marine insurance for the Arctic.

Finnish institutions and industry have experience with several of the above-mentioned points and these challenges can, therefore, be tackled with Finnish know-how, especially if Arctic shipping activity increases. AMSA (Arctic Council, 2009), for example, states that icebreaking technology will play an important role in Arctic shipping in the future. New Arctic shipping technologies also imply that independently-operated, icebreaking commercial ships could assume operations in the future. Obviously, changes in global trade, resource pricing (including oil prices), and the future development of competing routes (Suez Canal, Panama Canal, and the Trans-Siberian railroad as the most significant ones) will also affect the attractiveness of the Arctic shipping lanes.

3.6.1 The Northwest and Northeast Passages

The Northwest Passage consists of various maritime routes between the Atlantic and Pacific oceans along the northern coast of Northern America in the Canadian Arctic Archipelago (Arctic Council, 2009, see Fig. 7). The Canadian Arctic Archipelago comprises 36.000 islands which are sparsely populated with less than 30.000 inhabitants. Many ecologically sensitive areas exist throughout the region. Additionally, there are many narrow and shallow areas in the Archipelago, many of which are uncharted. Ice is present most of the year and thus presents a challenge for maritime navigation.

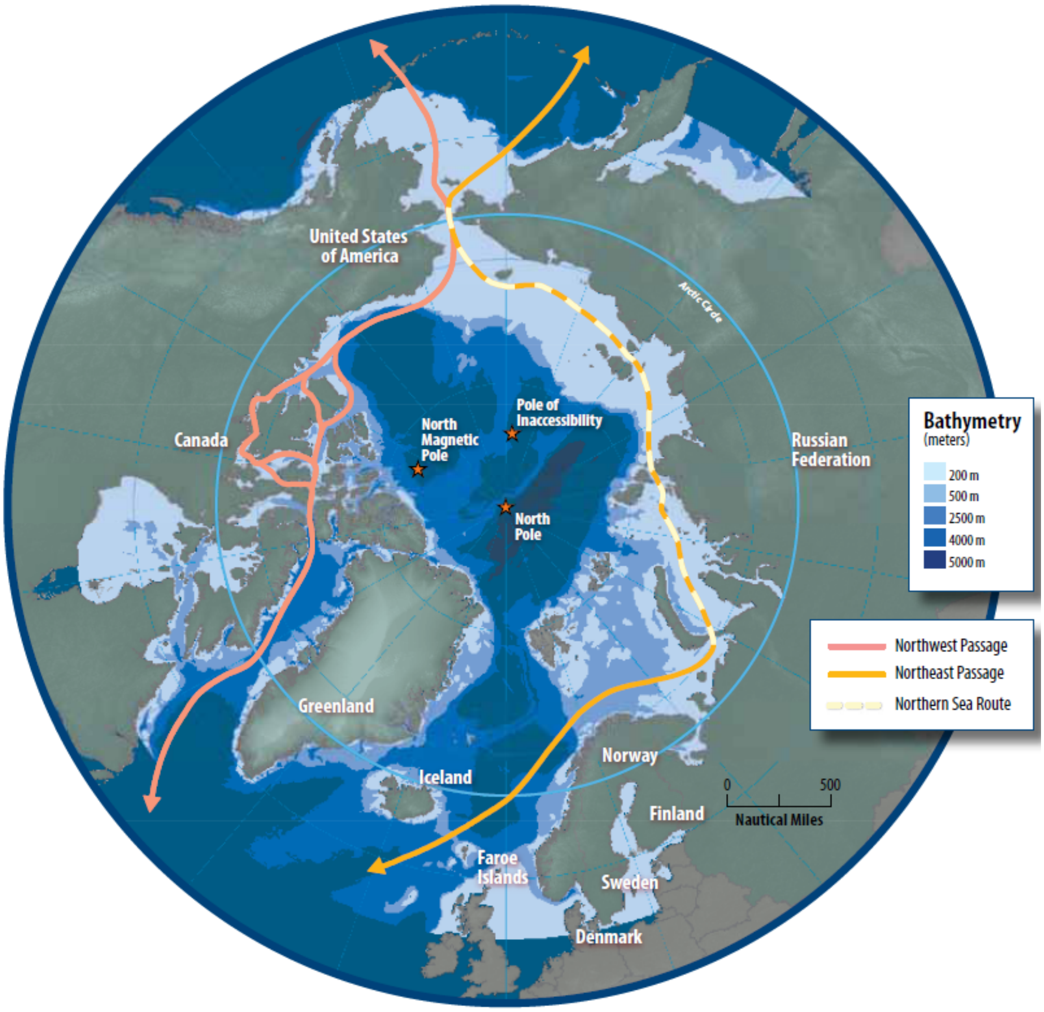
The sea ice conditions in the Canadian Arctic have shown negative trends in coverage for the past three decades with a high year-to-year variability in all regions (Arctic Council, 2009). In the changing climate, the Canadian Arctic Archipelago is, however, expected to be one of the last areas of the Arctic Ocean to have significant summer ice cover. In spite of more favorable ice situations in the summer, sea ice will be present throughout the most part of the year (approximately nine months out of the year), and therefore, access to the Northwest Passage will continue to be controlled by ice conditions (Arctic Council, 2009).

Somanathan et al. (2006) modeled the Northwest Passage and found it economically favorable compared with the traditional route through the Panama Canal between harbors in eastern Canada and northeastern Asia. AMSA (Arctic Council, 2009) has estimated, in turn, that most of the Arctic travel by 2020 will still be destinational rather than trans-Arctic. Destinational shipping activities are projected to rise due to an increase in the re-supply to the Arctic communities, expanding resource development, and tourism. AMSA (Arctic Council, 2009) concludes that the Northwest Passage is not expected to have become a viable trans-Arctic route by 2020 due to the uncertainty in conditions, e.g., seasonal variability, ice conditions, a complex archipelago, lack of adequate charts, and high insurance and other costs.

In contrast, Verny & Grigentin (2009) conclude that the Northeast Passage is a viable alternative transit route compared with the shipping lanes through the Suez Canal (the Royal Route) and the Trans-Siberian railroad. However, they estimate that the respective costs would be 100% and 30% higher for the Northeast Passage than on the Royal Route and the Trans-Siberian. Shipping and fuel costs accounted for over 90 percent of the total Northeast Passage operating costs.

With regard to the Northern Sea Route (NSR) or the Northeast Passage, AMSA (Arctic Council, 2009) asserts that the transport of oil from the Pechora Sea to Europe is both technologically and economically feasible, and that the cargo flow today is more than 1.5 million tons per year. By 2020, the traffic volumes on the NSR are expected to increase to 40 million tons. The higher traffic volumes will lower the operating charges which are now relatively high for the NSR compared with, for example, the Baltic Sea. The AMSA report (Arctic Council, 2009) estimated that if the proper technologies are developed and implemented, maritime transport costs of oil and gas could be lower than they are for pipeline transportation.

Figure 7 The Arctic Marine Area.



Source: Arctic Council, 2009.

3.7 Ice conditions in the Arctic Sea Route and projected change in the 2030s and at the end of the 21st century; The point of view of the Arctic and Antarctic Research Institute

The Arctic Sea Route (ASR) consists of navigable routes mainly through the Russian Arctic, stretching from the Barents Sea (Kirkanes in Norway) in the west to the Bering Strait in the east. The ASR is the shortest route connecting northwestern Europe and South-East Asia. The length of the ASR between the Kara Gate Strait and Bering Strait is approximately 3000 miles. Using the ASR shortens the distance between Hamburg and Yokohama by nearly twice, and the shipping time by 10–14 days compared with the Suez Canal route. However, navigation on the ASR is obstructed by sea ice. The entire ASR is covered by ice in winter while some parts – particularly in the Laptev Sea and East Siberian Sea – are covered by ice even in summer. Hence, an ice-breaker fleet is required to ensure the safety and profitability of the shipping industry.

The maximum cargo transportation along the ASR was reached by the end of the 1980s with a level of 5.5–6.5 million tons. This amount has been declining considerably over the last two decades (by~2.5 times in western part of the ASR and by~30 times in its eastern part, mostly due to Russia's economic decline (for further details, see Plaksy, 2008).

3.7.1 Ice conditions in the Eurasian Arctic Seas

A short review of the past and current ice conditions of the Arctic Seas is presented here based on ice maps which were developed by the Arctic and Antarctic Research Institute (St. Petersburg, Russia). These maps are based on regular aerial ice visual and photo reconnaissance (1933–1979), joint visual and photo reconnaissance, and satellites (1980–1990). Since 1990, ice maps based entirely on satellite data have been produced. These maps present the areas of ice distribution (ice cover) and the areas of ice tract (i.e., areas with an ice covering of 70–100%).

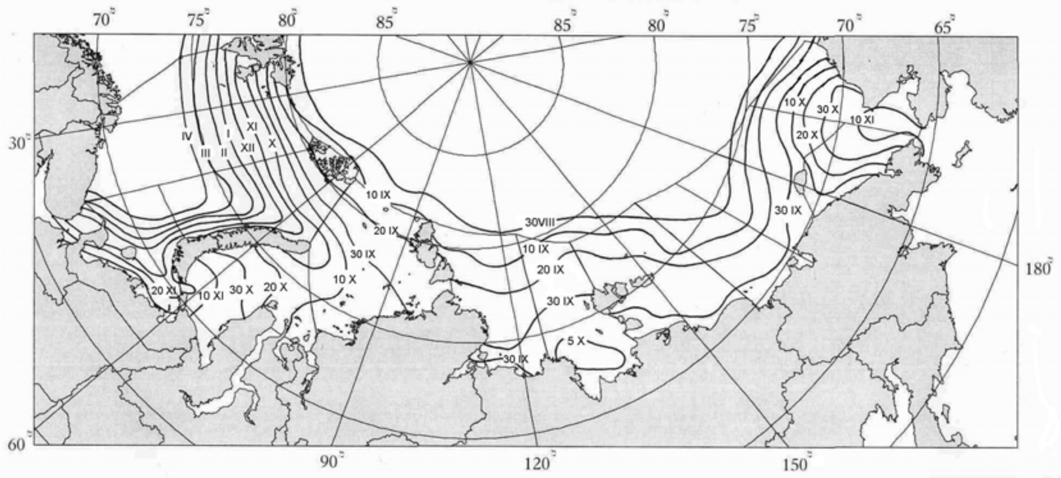
Processes of ice generation and growth take place over a period of approximately seven months (October to May) within the annual cycle of ice conditions in the Arctic Seas. During this period, all seas of the Siberian shelf are completely covered by ice of different ages (90–100% of the area). Fast ice is generated in shallow coastal regions. Ice breakup begins at the end of May – beginning of June.

3.7.1.1 Specifics of ice conditions during fall and winter

Ice generation and growth. Fall and winter represent the most important seasons in the annual cycle of the seasonal dynamics of ice conditions in the Arctic. Primary ice formations (ice needles, studgy ice, etc.) on ice-free water usually develop at the end of August – beginning of September. Steady ice formation refers to the time it takes for primary forms of ice to develop into steady ice. Early periods of ice formation usually predetermine the complexity of ice conditions during winter.

The general characteristics of the temporal distribution of ice formation are presented in a map of isochrones with an average of many years of steady ice formation times (Fig. 8).

Figure 8 Average times of steady ice formation in the Arctic Seas.



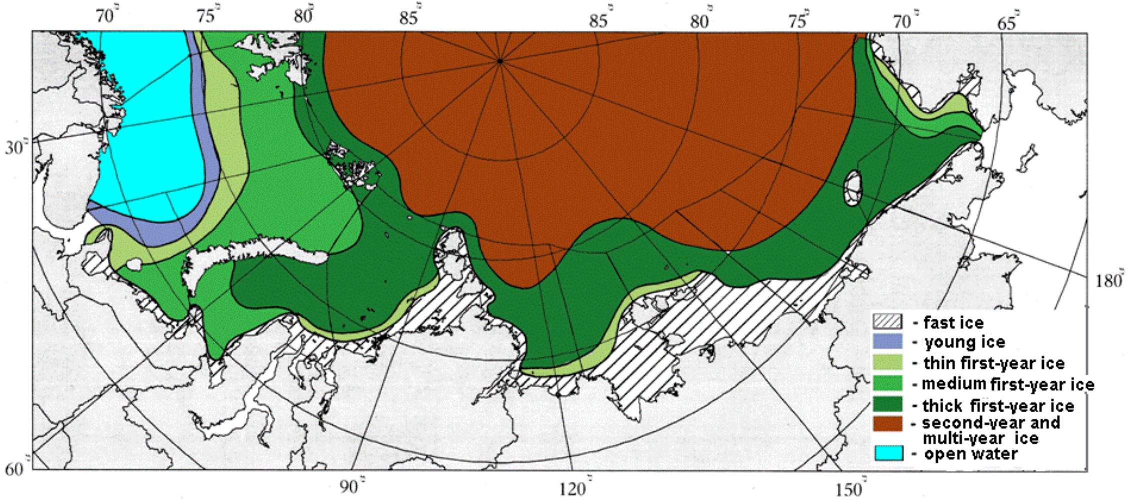
Steady ice formation begins at the end of August, north of the East Siberian Sea, and north of the Kara and the Laptev Seas in the first week of September, and continues to form north of the East Siberian Sea by September 20th. Ice formation in shallow coastal zones begins in early October. On average, the Laptev and East Siberian Seas are frozen within 35–40 days, the Kara and Chukchi Seas within 80–85 days. The time of steady ice formation varies considerably (from 30 to 80 days), particularly in regions affected by the advection of water from warmer regions. The depth of the ice increases in accordance with its age: Nilas (up to 10 cm), grey ice (between 10 and 15 cm), grey-white (15 to 30 cm) [these three types are usually referred to as 'young ice'], one-year thin ice (30 to 70 cm), one-year medium ice (70 to 120 cm) and one-year thick ice (with a depth of > 120 cm). Two- and many-year ice is found in northern parts of the Arctic Seas. The thickness of the ice cover is usually heterogeneous, owing to the migration of the ice field from the north.

Fast ice and ice-holes. A distinguishable feature of the Arctic Seas' ice regime is the occurrence of fast ice, i.e., immovable ice, mostly in shallow and island regions. The width of fast ice can reach hundreds of kilometers in the central Arctic Seas (Fig. 8). Fast ice develops until March or April. By then, fast ice covers, on average, 27% of the total ice cover of the seas of the Siberian shelf. The maximum thickness of fast ice is 190–210 cm, on average, for the Laptev and East Siberia Seas, 150–160 cm west of the Kara Sea, and 170 cm south of the Chukchi Sea.

Ice holes form along the entire boundary of fast ice, namely, between fast and drifting ice. Ice holes consist of areas of free water or young ice, with a width ranging from tens to hundreds of kilometers. They either exist permanently or sporadically. The stability of ice holes is classified by their recurrence: >75% are stationary ice-holes (e.g., south of the Kara and Laptev Seas), 50 to 74% are stable, and <50% are sporadic (west of the East Siberian and Chukchi Seas).

By the end of the ice cover formation period (usually May), one-year ice with a thickness of >120 cm has developed, covering around 60 to 85% of the area of the Arctic Seas. Two- and many-year old ice is widespread in the East Siberian, Laptev and Chukchi Seas (Fig. 9).

Figure 9 Average distribution of the age of ice in the Arctic Seas by the end of the growth period of ice cover.

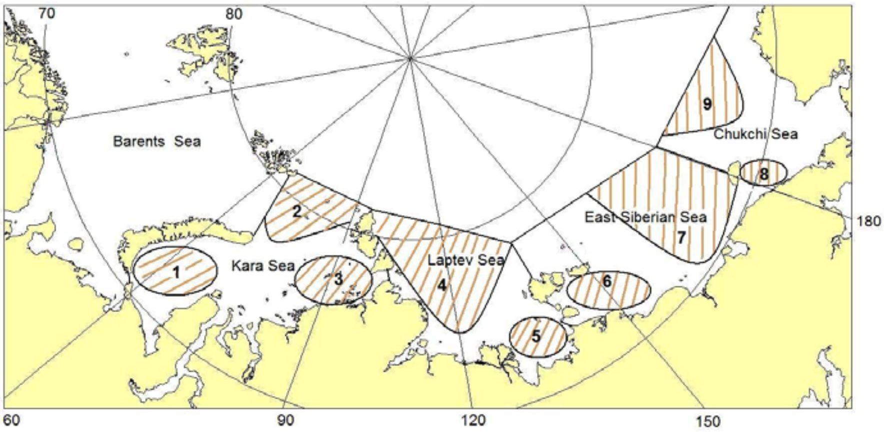


3.7.2 Ice conditions during spring and summer

Destruction of ice cover. The thawing of ice begins in mid-May – second week of June. In principle, all types of ice thaw by the end of summer, aside from thick one-year ice, old ice, and pack ice. Fast ice usually thaws within 1 to 2 weeks in July. The disintegration of the ice cover occurs together with its destruction and is attributable to heat and dynamic processes. This leads to the development of zones of different ice density: Rare (1–3 tenths), sparse (4–6 tenths), dense (7–8 tenths) and very dense (9–10 tenths). Numerous years of observation have shown that a dense ice cover is usually formed in certain regions of the Arctic Sea. Such areas are referred to as ice tracts.

Ice tracts. The ice of ice tracts is distinguished by its considerable thickness and hummocky structure. Nine ice tracts exist in the Arctic Seas of the Siberian Shelf (Fig. 10). The Novaya Zemlya tract blocks shipping through the Novaya Zemlya Strait until the second half of August, as well as through the Severnaya Zemly Strait and the Vilkitsky Strait. The Taimir tract is the largest ice tract (approximately 30% of the region's area). Its ice can impede navigation over the entire summer. The Yana tract obstructs shipping from the East Siberian to the Laptev Sea through the Sannikov Strait and usually disintegrates by the end of August. The Novosibirsk tract does not cause any particular problems for navigation. The Ajon tract is the largest in the Arctic Seas, and consists of thick and pack ice. However, the ASR in this part of the Arctic is usually free of ice in August and September. The Kara North and Chukchi tracts are outside of the ASR.

Figure 10 Location of ice tracts in the Arctic Seas.*



**1 - Novaya Zemlya, 2 - Kara North, 3 -Severnaya Zemlya, 4 - Taimir, 5 -Jana, 6 -Novosibirsk, 7 -Ajon, 8 -Wrangel, 9 -Chukot North.*

Clearing of seas from ice. The most intensive clearing of the Arctic Seas from ice is observed in August, and lasts until the end of September (Table 4).

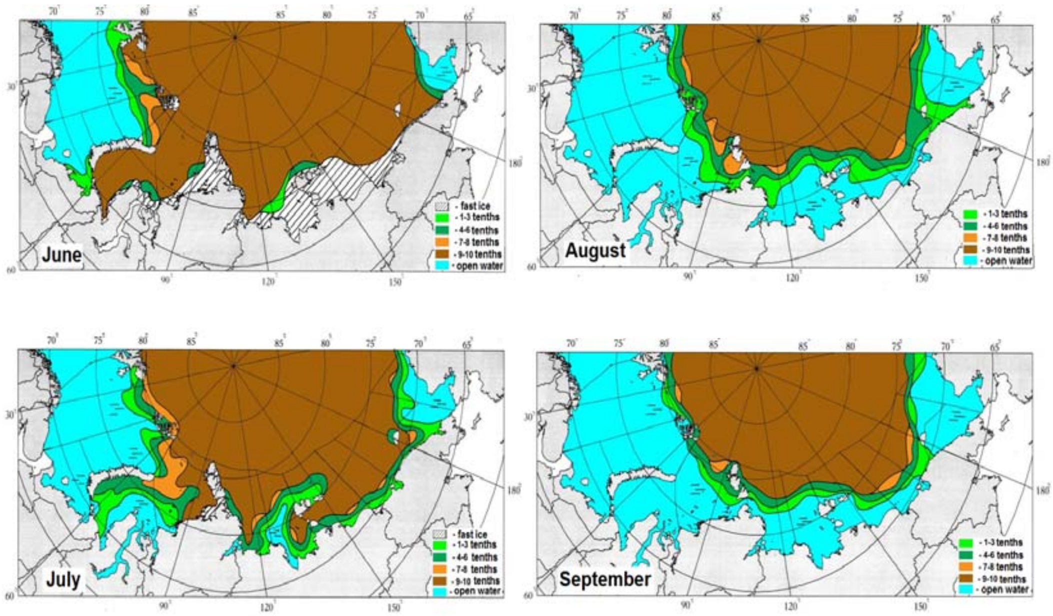
Table 4 Area of the Arctic Seas free from ice at the end of June to September in %.

Parts of the Sea	**Months**			
	VI	**VII**	**VIII**	**IX**
South-West of Kara Sea	17	50	90	97
North-East of Kara Sea	5	20	40	56
West of the Laptev Sea	10	23	46	48
East of Laptev Sea	10	31	74	84
West of East Siberian Sea	6	14	44	56
East of East Siberian Sea	2	7	20	30
South-West of Chukchi Sea	29	60	78	86

On average, before the beginning of ice formation, the South-West of the Kara Sea is nearly completely free of ice; the eastern part of the Laptev Sea is 84% and the southwestern part of the Chukchi Sea is 86% free of ice. Approximately 50% of the northeastern part of the Kara Sea and the western part of the Laptev and East Siberian Sea are free of ice prior to the onset of ice formation.

Distribution of ice in the summer. The distribution of the zones that are free of ice, as well as the ice fields of different density during the summer is illustrated in maps developed by the AARI, based on 10-day survey maps for 1933–1992.

Figure 11 Distribution of ice of different density in the Arctic Seas at the end of June to September (median value of a number of years).



3.7.3 Climatic variation in the Arctic and change in ice conditions in the Arctic Seas

Results of research carried out by AARI (Frolov et al., 2007, 2009) indicated that long-period changes of annual surface air temperature, ice cover density and other hydro-meteorological indicators in the Arctic during the 20th and beginning of the 21st centuries were characterized by the occurrence of several cycles with a duration of approx. 60, 20, 10 and less years. These cycles were observed along a quasi-linear warming trend over a time period of 200 years. The cited sources relied on natural drivers (primarily on the dynamics of incoming solar energy) and do not address the anthropogenic impact on the Earth's climate.

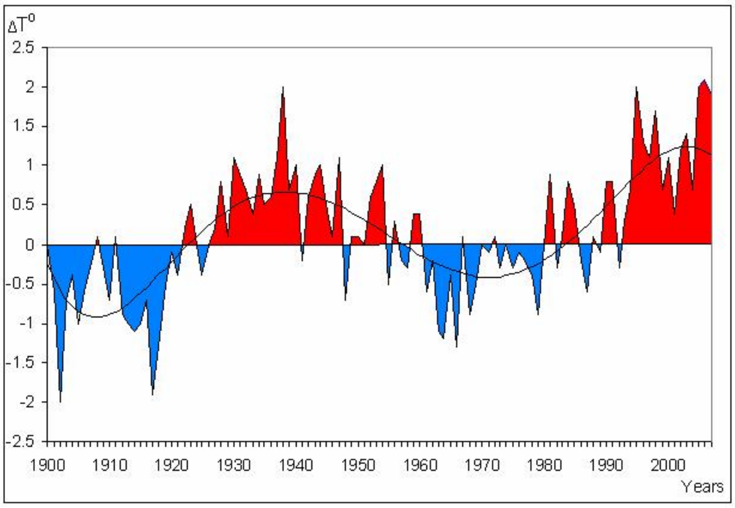
The results of the most influential 60-year cycle with reference to a change in the climatic system were clearly recognizable in the Arctic. However, they were also observed in different regions of the planet, including the Antarctic. Interchanging periods of warming and cooling during the 20th century identified by many researchers was connected to this cycle. The stable manifestation of this cycle in many natural processes in different regions of the Earth and during different time periods points to its common natural drivers.

From a global perspective, the Arctic demonstrated the greatest variability of natural processes throughout the entire 20th century. From the onset of the 20th century, the air temperature in the Arctic zone (70–85° N.L.) experienced a long-period of natural oscillations of which the 60-year cycle has clearly been recognized (Fig. 12). This cycle involves decreasing air temperatures at the beginning of the century; "warming" of the Arctic in the 1920s to 1940s with a peak in 1936–1938; cooling from 1960–1980s; and warming beginning in the middle of the 1990s and reaching its peak at the beginning of the 21st century.

Figure 12 demonstrates how the increased temperature impacted the hydro-meteorological and ice conditions in the Arctic from the beginning of the 1920s until the middle of the

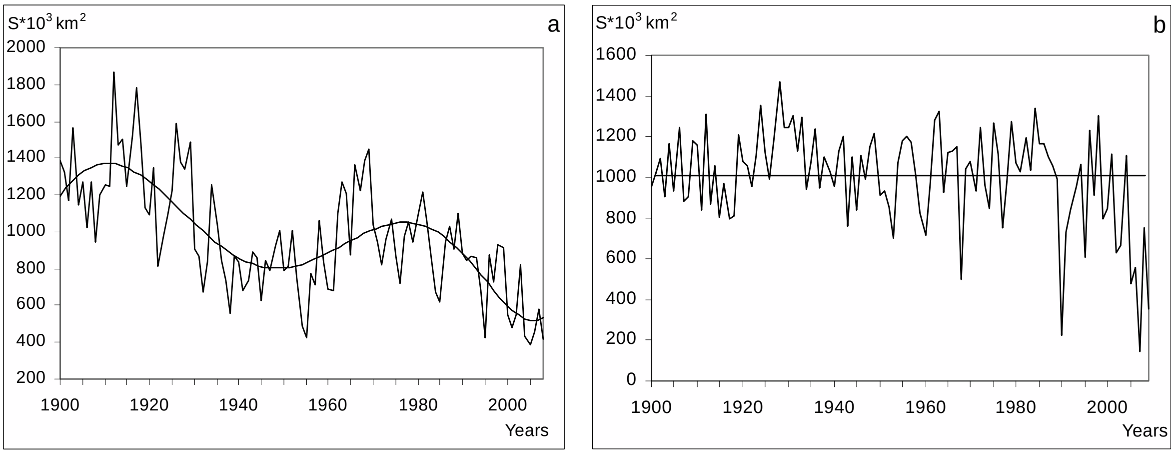
1950s: 1922–1956 represented the warm period, while 1957–1984 represented the cold period. Another warm period began in the mid-1980s and continues to this day.

Figure 12 Dynamics of anomalies of the annual average air temperature (°C) over the 70-85° northern latitudes of the Eurasian Arctic in the 20th/beginning of the 21st centuries and the 60-year cycle.



Changes in the Arctic Seas' ice cover during the 20th century were characterized by a negative linear trend around which the cyclic oscillations of 60, 20 and 10 years took place. These changes had spatial- and temporal-specific features (Frolov et al., 2007, 2009). In the Western Seas (the Greenland, Kara and Barents Seas), the negative linear trend of the ice cover was substantial and the main cycle has a length close to 60 years (Fig. 13). In the Eastern Seas (the Laptev, East Siberian, and Chukchi Seas), ice cover oscillations were observed around a long-term mean (excluding the last several years). The inter-annual variability of the ice cover in these regions was very high and the 60-year cycle has apparently become weaker.

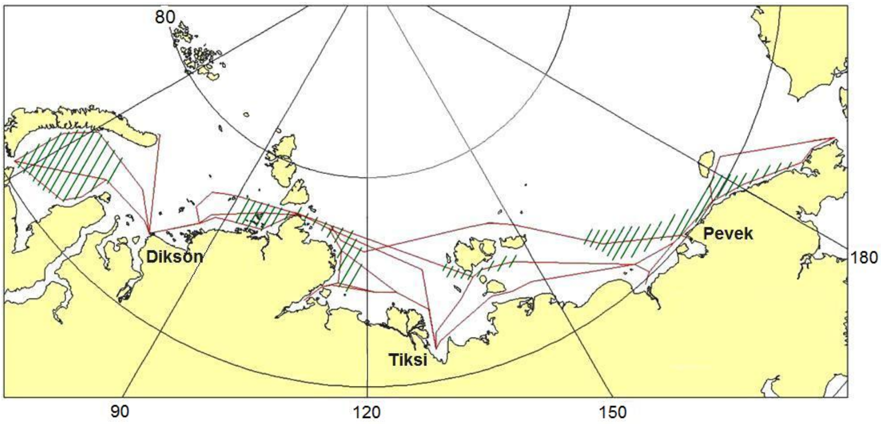
Figure 13 Dynamics of the area of ice: ***a*** – in Western (Greenland, Barents, Kara), ***b*** – in Eastern (Laptevich, East Siberian, Chukchi) Seas in 2008.



3.7.4 Recurrence of ice conditions over the ASR under different climatic conditions

Shipping over the entire ASR is possible in summer and fall, and throughout the entire year in the Kara Sea. Major transport routes and regions in which the navigation of ships and even of ice-breakers is quite difficult are illustrated in Figure 14. These difficulties are attributable to large ice tracts and extensive areas of fast ice.

Figure 14 Major routes of the ASR and regions with unfavorable ice conditions.



Ice density and ice tracts. The ice conditions that pose challenges to the navigation in the seas of the ASR are characterized by two indicators: Ice density (i.e., the area of the ice covering water) and the area of dense ice (7 to 10 tenths) in ice tracts. Both indicators are calculated in percentage of the sea's areas or in square kilometers. Data that have been used for the analysis of ice conditions in the Arctic are presented in Table 5. These data are based on observations that were provided in 1933–2009 (data for August). Table 5 provides many-year variability of ice density in Kara, Laptev and East Siberia Seas.

Table 5 Ice density in the Arctic Seas between 1933–2009.

Indicators	Seas			
	Kara	Laptev	East Siberian	Chukchi
Number of years	77	77	77	77
Average ice density, in %	46	50	76	32
Maximum, %	92	90	98	57
Minimal, %	5	8	10	0
Amplitude (A), %	87	82	88	57
1/5A, %	17	16	18	11

The complexity of ice conditions was estimated using a criterion which is equal to 20% of the amplitude (A) of many-year oscillations: Heavy conditions correspond to a range of > M +0.2A, average conditions to M±0.2A, and light conditions to < M-0.2A. The recurrence of these types of ice conditions is presented in Table 6. Average ice conditions were the most frequent (the recurrence varies from 51 to 65%). Heavy and light conditions had a similar rate of recurrence (19–27% and 16–23%, respectively, see Table 6).

Table 6 Number of years (N) and recurrence (P) of different types of ice conditions during 1933–2009, %.

Type of ice conditions	Seas							
	Kara		Laptev		East Siberian		Chukchi	
	N	P, %	N	P, %	N	P, %	N	P, %
Heavy	15	19	20	26	15	19	21	27
Light	14	18	18	23	12	16	16	21
Average	48	62	39	51	50	65	40	52

Tables 7 and 8 present an analysis of the recurrence of types of ice conditions classified in the "warm" (1930–1956 and 1985–2009) and "cold" (1957–1984) periods. These data reveal that average ice conditions dominate all climatic periods (recurrence of 63%). Both the "warm" and "cold" periods have heavy and light ice conditions. Evidently, heavy conditions dominate during "cold periods" (the average ratio heavy/light for all seas is 35/11).

Table 7 Number of years (N) and recurrence (P) of types of ice conditions during different climate periods.

Periods and years	N	Types of ice conditions					
		Heavy		Light		Average	
		N	P, %	N	P, %	N	P, %
The Kara Sea							
«Warm», 1933–1956, 1985–2009	49	4	8	16	33	29	59
«Cold», 1957–1984	28	11	39	1	4	16	57
The Laptev Sea							
«Warm», 1933–1956, 1985–2009	49	12	24	12	24	25	52
«Cold», 1957–1984	28	8	29	6	21	14	50
The East Siberian Sea							
«Warm», 1933–1956, 1985–2009	49	5	10	13	27	31	63
«Cold», 1957–1984	28	11	39	1	4	16	57
The Chukchi Sea							
«Warm», 1933–1956, 1985–2009	49	11	22	13	26	25	51
«Cold», 1957–1984	28	9	32	3	11	16	57

During the "warm" periods, the recurrence of years with light ice conditions is most clearly observed in the Kara Sea (light/ heavy = 33/8) and in the East Siberian Sea (27/10). This ratio is not clear, and a high recurrence of heavy conditions is observed here as well. The overall average light to heavy conditions during the "warm" periods is 27/16.

Table 8 Number of years (N) and recurrence (P) of types of development of ice tracts during different climatic periods.

Climatic periods	N	Type of ice conditions					
		Heavy		Light		Average	
		N	P, %	N	P, %	N	P, %
Movaya Zemlya ice tract							
«Warm», 1938–1956, 1985–2009	44	7	16	17	39	20	45
«Cold», 1957–1984	28	12	43	3	11	13	46
Severnaya Zemlya ice tract							
«Warm», 1938–1956, 1985–2009	44	6	14	18	41	20	45
«Cold», 1957–1984	28	13	46	3	11	12	43
Taimir ice tract							
«Warm», 1938–1956, 1985–2009	44	8	18	14	32	22	50
«Cold», 1957–1984	28	7	25	4	14	17	61
Jana ice tract							
«Warm», 1938–1956, 1985–2009	42	6	14	12	29	24	57
«Cold», 1957–1984	28	9	32	6	21	13	47
Novosibirsk ice tract							
«Warm», 1938–1956, 1985–2009	42	7	17	14	33	21	50
«Cold», 1957–1984	28	13	46	9	32	6	22
Ajon ice tract							
«Warm», 1938–1956, 1985–2009	36	9	25	9	25	18	50
«Cold», 1957–1984	28	8	29	3	11	17	60
Wrangel ice tract							
«Warm», 1938–1956, 1985–2009	43	9	21	17	39	17	40
«Cold», 1957–1984	28	7	25	6	21	15	54

Average conditions dominate during all climate periods (40 to 60%). Higher positive anomalies of large areas of ice tracts are observed during the "cold" period (large positive anomalies to large negative anomalies = 35/16) and vice versa for "warm" periods (15/34).

Navigation without ice-breakers along the entire ASR. The duration of the period during which navigation is possible and when no ice breakers are found along the entire ASR from the Kara Gate to the Bering Strait is very important. The duration of this period depends on the presence of dense ice, which could appear at individual sites of the ASR, even during light ice conditions (see Fig. 15).

The duration of the period during which navigation along the entire ASR is possible (for ships in ice class) and when no ice breakers are required is illustrated in Figure 15. This figure indicates that there were years when such navigation was not possible, even during recent "warm" periods (1993, 1997, 2001).

Figure 15 Duration of the period when navigation was possible along the entire ASR without ice breakers in decades (1940–2009) for ships in class UL (LU5) (dotted line = the trend approximated by a polynomial of the 3rd power)

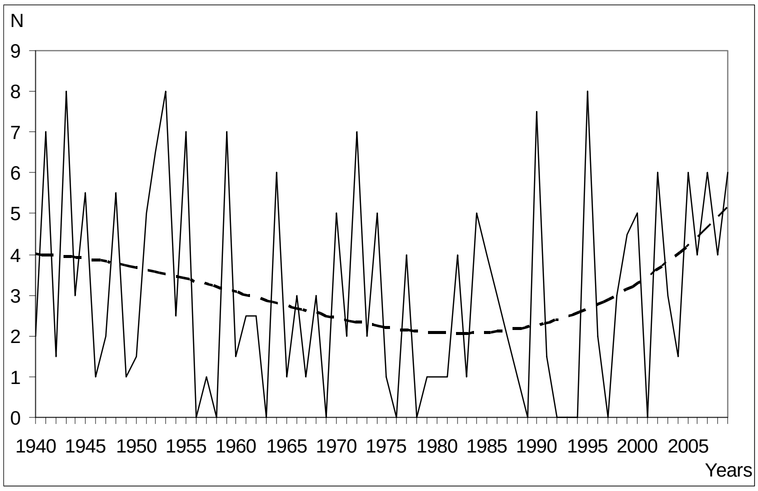


Table 9 presents the recurrence of different navigation conditions between 1940 and 2009: Unfavorable conditions refer to conditions under which shipping without ice-breakers was completely impossible (or only possible for one decade) (33%); favorable conditions refer to conditions in which through-shipping was possible for over 4 decades (51%), and medium conditions are those in which the period of possible shipping comprised 1.5 to 3.5 decades (23%).

Table 9 Recurrence of shipping without ice-breakers along the entire ASR from 1940 to 2009.

Navigation conditions	Length of shipping without ice breakers, decades	Number of years	Recurrence in %
Favorable	4–8	27	51
Medium	1,5–3,5	20	16
Unfavorable	0–1	23	33

During the "warm" periods, the recurrence of favorable conditions was about two times higher than the recurrence of the unfavorable ones (Table 10).

Table 10 Number of years (N) and recurrence (P) of shipping without ice-breakers along the entire ASR during the different climatic periods.

Climatic periods	N	Type of ice conditions					
		Favorable		Medium		Unfavorable	
		N	P, %	N	P, %	N	P, %
«Warm», 1940–1956, 1985–2009	42	19	45	13	31	10	24
«Cold», 1957–1984	28	8	29	7	25	13	46

3.8 Prediction of ice conditions for 2030–2040 and by the end of the 21st century (forecast by the Arctic and Antarctic Research Institute)

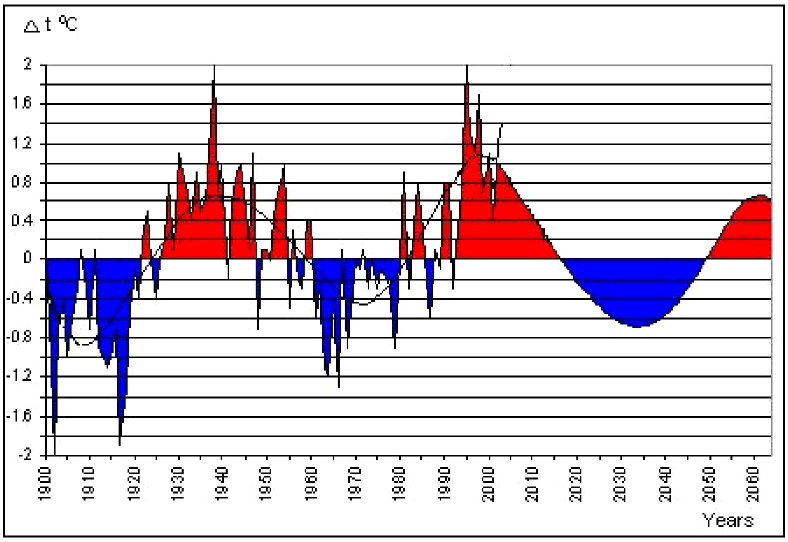
The stable character of the natural 60-year cycle of changes in air temperature in the Arctic throughout the 20th century (and for longer periods in other regions of the planet) provides the foundation for climatic change forecasts of AARI in the Arctic during the 21st century (Figure 16).

Based on a physical-statistical approach and averages for the 20st century amplitude of the 60-year cycle, experts from AARI developed a background forecast of the dynamics of annual air temperature and ice cover of the Arctic Seas for the next few decades (Frolov et al., 2007, 2009).

According to this forecast, it is expected that the development of hydro-meteorological and ice conditions in the Eurasian Arctic will, over the next 5 to 10 years, be based on elevated temperatures with a gradual decrease by 2015, similar to the situation observed at the end of the 1st warming of the Arctic.

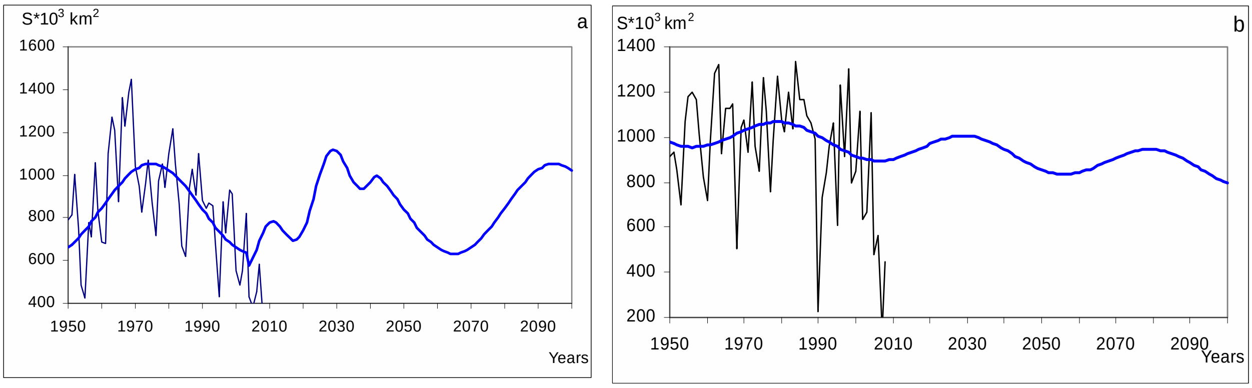
A further decrease in the temperature is expected until approximately the mid-2030s to 2040s. The transition to the next warm period is expected thereafter. This warm period will have a limited duration and its peak is expected in the mid-2060s. By the end of this century, the next cycle of decreasing temperatures is predicted to begin.

Figure 16 Change in anomalies of average annual temperature across 70-85° northern latitudes in the 20th – beginning of the 21st century and the forecast for the 21st century



The forecast of probable dynamics of ice cover in the Arctic regions in the 21st century is presented in Figure 17. This forecast is based on long-period cycling observed in the Arctic. Two major components which have contributed to the long-period variability of the ice area in the 21st century have been used to develop the forecast: 60- and 20- year cycles for seas of the western region (the Greenland Sea, the Barents Sea, and the Kara Sea), and 60-year cycles for the Eastern Seas (Laptev Sea, East Siberian Sea, and Chukchi Sea).

Figure 17 The forecast of change of the total area of ice in the Western (a) and Eastern Seas during the 21st century in August.



This forecast predicts the continuation (not trend) of the oscillatory character of the dynamics of the ice area in the Arctic Seas. During the period 2020–2040, it is expected that the ice area will increase during the summer, reaching its peak in 2030–2035 in the Eastern Seas and in 2035 in the Western Seas. The second peak is likely to occur around 2090–2095. The period of lower ice cover is expected in 2050–2070 and at the beginning of the 22nd century.

One major conclusion of this forecast presented by AARI is that, when taking into account regional specifics of climate cycles and long-period trends, a continuation (not trend) of the oscillatory character of the dynamics of climatic change in the Arctic takes place. This projection contradicts the conclusion of the IPCC AR4, which predicts a dramatic shrinking and even disappearance of the ice cover along the ASR, beginning as early as the 2050s.

3.9 Discussion

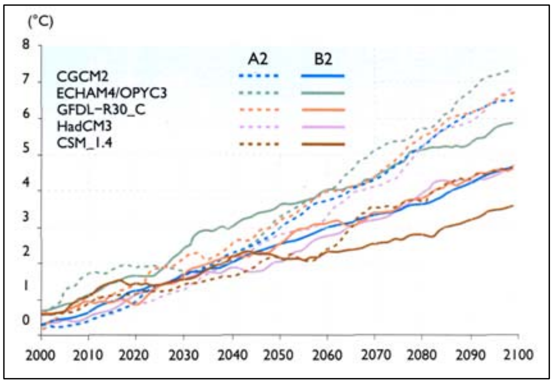
The forecast of climatic and ice conditions developed by the Russian Arctic and Antarctic Institute is based on interchanging "warm" and "cold" periods.

During the "cold" period **2020–2040:** This projection anticipates an increase in the areas of ice in the Arctic Seas over the summer months, with a peak around 2030–2035, an increasing frequency of difficult ice conditions with an elevated recurrence of large positive anomalies of areas of ice tracts, and an increasing recurrence of years of unfavorable conditions for shipping along the entire ASR without ice-breakers.

During the subsequent "warm" period **2050–2070:** a lower level of ice density is expected, an increasing recurrence of light ice conditions and large negative anomalies of the areas of ice tracts, an increasing recurrence of favorable conditions for shipping along the entire ASR without ice-breakers.

This forecast thus contradicts the predictions of the IPCC, which are based on AOGCMs. In Chapter 3.1, we addressed the uncertainties of any climatic predictions for the Arctic. A substantial number of scientists shares the opinion that "data of observation […] do not contain any clear signal of anthropogenic conditionality of climate change" and "results of numerical modeling of the climate which prove the greenhouse warming hypothesis and which supposedly are in tune with observational data, in reality are not more than adjustment to data of observation" (Kondratiev, 2004, p.121). Thus, alternative opinions should be considered, at least to complete the picture.

Figure 18 Forecast of anomalies of surface temperature for high latitudes (60 ºN.L. to the North Pole) during the 21st century (deviation from the average for 1980–2000) by different AOGCMs .



Source: ACIA, 2005.

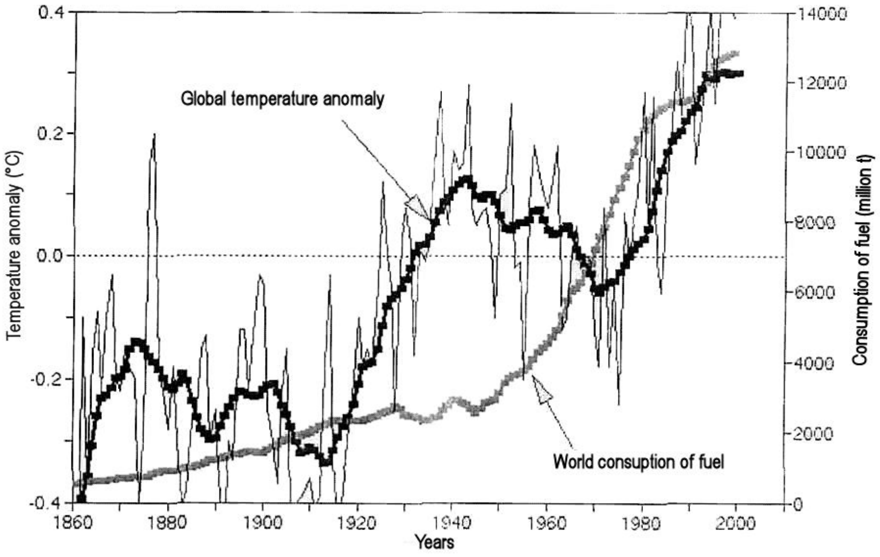
The noteworthy evidence the proponents base their alternative hypothesis on global warming on are as follows:

- large variation and inconsistencies between the different AOGCMs (the increase in annual temperature for high latitudes by different models by the year 2100 ranges from 3.5 to 7 °C, Fig. 18);
- none of the models are able to explain the Arctic warming in the 1920–1940s which is not linked to the greenhouse effect;
- validation of the models is often provided for the last decades but not for the entire period of climatic observation;
- practically all "conventional" publications ignore natural oscillations of hydro-meteorological processes and phenomena of which input in many-year variability of climate is substantially higher than the anthropogenic impact on current climate;
- inconsistency of temporal change of anthropogenic carbon emissions and global warming: Any direct connection between global consumption of fuel and global warming in the 20th century was absent (Fig. 19, Klyashtorin and Lyubushin, 2003);
- anomalies of the surface air temperature in the Arctic zone (70-85° N.L.) support the cycling decrease according to this forecast: 2007 (the warmest year in the Arctic during the current period of warming) -2,2° in 2008, –2,0° in 2009 г. – 1,7°; the active layer on permafrost decreased by 25% comparatively with 2008 and by 20% to the average for the last decade; overall Russia the temperature anomaly was +0.55 °C (23rd rank from 1936) (Federal Service on Hydrometereology and Monitoring of Environment of the Russian Federation, 2010);
- opposite climatic tendencies in the Arctic and Antarctic, and, as a consequence, an increase in the area of sea ice in the Antarctic (Fig. 20, Gudkovich et al., 2008);
- a number of other (aside from temperature) indicators of general circulation of the atmosphere, as well as the dynamics of the area of ice indicates a tendency toward cooling during the last years (Frolov et al., 2008); the minimal area of ice was observed in 2007; subsequently, it began to increase again (. 11).

Table 11 Area of ice in the Arctic Sea in September 2007–2009.

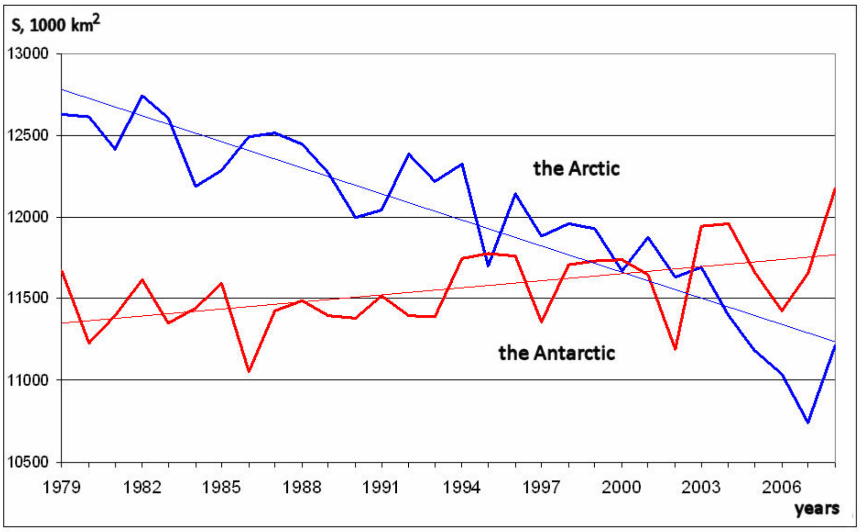
Years	S million m^2	Anomalies, million m^2	
		from average	from 2007
1978–2009	6.584	–	–
2007	4.345	–2.239	–
2008	4.706	–1.878	+0.361
2009	5.200	–1.384	+0,855

Figure 19 Dynamics of global temperature anomalies and global fuel consumption from 1860–2000.



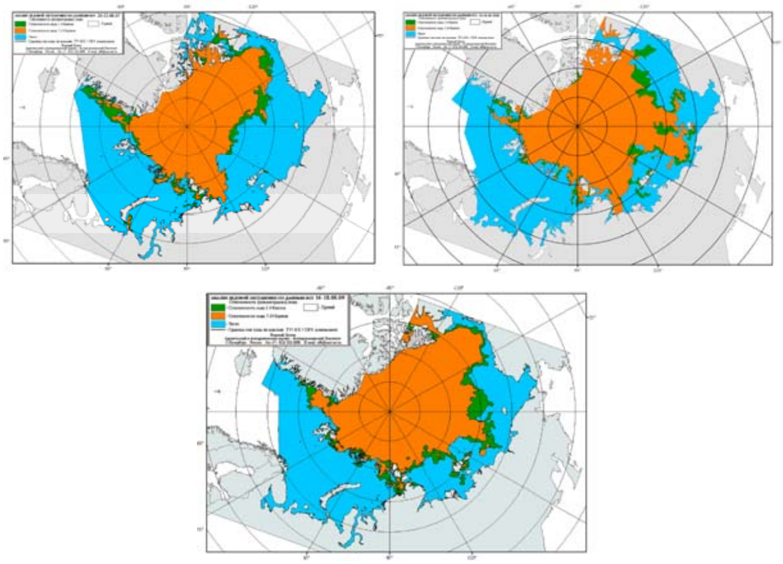
Source: Klyashtorin and Lyubushin, 2003.

Figure 20 Change of average areas of ice in the Arctic and Antarctic in 1979–2008 based on data of SSMR-SSM/I, algorithm NASATEAM.



As a result of the ongoing warming, light ice conditions are being observed in the Arctic Seas. Nevertheless, some parts of the ASR are blocked by ice tracts each year and ice-breakers are required for passage. The minimal area of ice in the Arctic was observed in 2007 (Fig. 20), while the Taimyr ice tract blocked the eastern route to the Vilkitsky Trait. The same situation was observed in 2008; moreover, ice of the Ajon ice tract blocked the eastern part of the East Siberian Sea for nearly the entire navigation period in 2008–2009 (Fig. 21).

Figure 21 Ice area in the Arctic Ocean in August of 2007–2009.



The authors of this projection perceive the rising trend in air temperature in the Northern Hemisphere in the 20th–21st centuries to be part of the multi-century cycle with a duration of 180–200 years (Bashkirzev & Mashich, 2004; Raspopov et al., 2004). According to the astronomer Abdusamatov (2009), the peak of this cycle was reached at the end of the 20th – beginning of the 21st century. Our forecast predicts that the next, nineteenth Little Ice-Age Period will set in between approximately 2055–2060 (±11).

The above forecast as an alternative to the "greenhouse theory" to understand the major drivers of the ongoing and future climatic change considers the impact on the Earth's atmosphere of the changes of the Total Solar Irradiance (TSI). This includes electromagnetic waves of different lengths, solar activity which causes solar wind, and cosmic race which are regulated by inter-planet magnetic fields. Indirectly, the impacts of solar activity become apparent in the coincidence of the average duration of the cycles recognized in the dynamics of air temperature, ice density and solar activity – 11 years cycle, 22 years cycle and approximately 60 years cycles, as well as the "200-year cycle" (Bashkirtsev & Mashich, 2004, Raspopov et al., 2004).

Figure 22 Comparison of change in average annual anomalies of air temperature (ΔT°) for the zone north of 62° N.L. with change in solar irradiation (left, linear trends and polynomial approximation) and CO_2 content in the atmosphere.

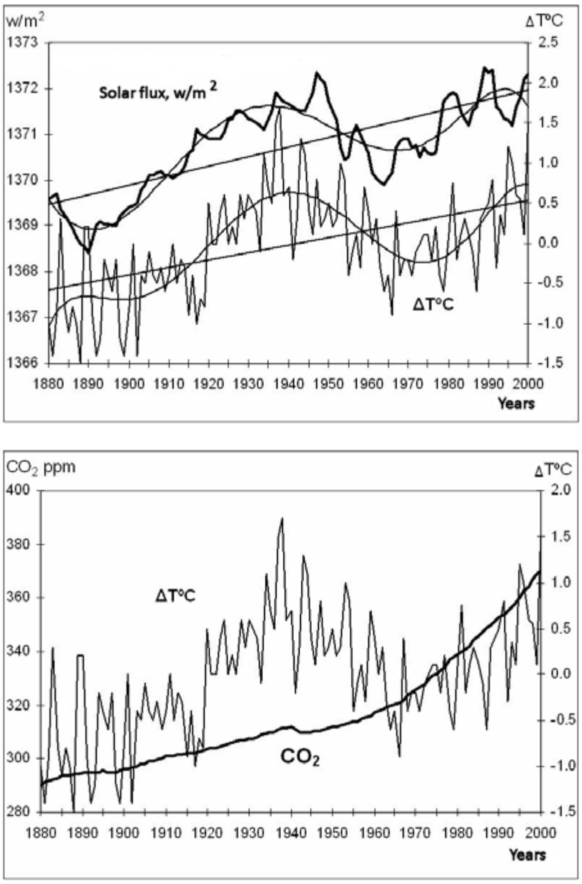


Figure 22 presents the dynamics of the annual anomalies of the surface air temperature and TSI received as a composition of the observation of sun-spots and total sun radiation (Hoyt and Schatten, 1993), as well as the concentration of CO_2 in the atmosphere in 1880–2000 (Soon, 2005) in high latitudes (north of 62° N.L.). These graphs are fairly consistent in recognizing a century positive trend and quasi-sixty-year cyclic oscillations; the dynamics of CO_2 has a different character. Figure 21 indicates that the amplitude of change of the full solar energy is around 4.0 W/m^2, or 0.3% of the solar constant. The 60-year cycle in the Arctic is explained by the impacts of the dissymmetry of the solar system (Frolov et al., 2007, Frolov et al., 2009). The impacts of the dissymmetry can be realized through solar activity and due to changes in distance between the sun and the Earth (Gudkovich et al., 2005). This also explains the recognized increase in the role of the 60-year cycle in the latitudinal direction and the opposite impact on climatic change in the Arctic and Antarctic (due to opposing signs of corresponding anomalies in perihelion and aphelion).

4 ARCTIC CLIMATE CHANGE AND THE ROLE OF SHORT-LIVED CLIMATE FORCERS

4.1 Introduction

Arctic temperatures have increased at almost twice the global average rate over the past 100 years (IPCC, 2007). From 1954 to 2003, annual average surface air temperatures increased from 2 to 3 °C in Alaska and Siberia during winter months (ACIA, 2004). Warming in the arctic has been accompanied by an earlier onset of spring melt, a lengthening of the melt season, and a net loss of the Greenland ice sheet. The lengthening of the melt season changes the Earth's albedo, a positive feedback effect which leads to further warming. Arctic warming is thus primarily a manifestation of global warming.

Reductions in the atmospheric burden of CO_2 should form the basis for any meaningful effort to mitigate climate forcing. But even if swift and profound reductions were achieved, the reductions would not necessarily delay the rapid melting of the Arctic, owing to the long life time of CO_2 in the atmosphere. However, there are shorter-lived climate forcing agents (SLCF) than CO_2, including primarily black carbon aerosol (BC, commonly known as "soot"), tropospheric ozone, and methane (CH_4). Due to shorter residence time in the atmosphere than CO_2 (e.g., days to weeks for BC and 9 years for CH_4), the reductions in their concentrations would be felt much sooner than the reduction of long-lived greenhouse gases (Quinn et al., 2008; Schindell & Faluvegi, 2009; Klimont, 2009). A strategy to reduce SLCF (along with CO_2) has been proposed by the scientific community (Hansen and Sato, 2001; Jackson, 2009; Molina et al., 2009) and more recently, has entered policy discussions, emphasizing the role of black carbon (AC-SAO, 2009; UNECE, 2009).

IIASA has been actively involved in SLCF for a number of years through its research on air pollution, and has recently become engaged in work with the Arctic Council. In preparation for the Arctic Ministers' meeting in late April 2009, IIASA co-authored the Draft White Paper "Current Policies, Emission Trends and Mitigation Options for Black Carbon in the Arctic Region" (Sarofim et al., 2009). This paper was discussed by both Arctic Ministers, as well as at the International Melting Ice Conference. Under the current AMAP work plan for the period 2009–2011, the following tasks referring to the non-CO_2 drivers of climate change are listed (http://arctic-council.org/working_group/amap):

- Continue to assess the state of science on SLCF and their impact on the Arctic;
- Identify gaps in observations of non-CO_2 drivers and promote new observations to fill those gaps;
- Assess and seek to improve the capacity of climate models to address short-lived climate forcers.

IIASA continues to be involved in the work of both the Arctic Council Task Force on SLCF and the AMAP Expert Group on SLCF. The research expands beyond black carbon by considering precursors of tropospheric ozone, including methane. A major contribution of IIASA will be to apply the GAINS model to project the effect of current and forthcoming air quality policies, specifically those implemented to reduce particulate matter emissions, as these will considerably reduce BC. GAINS results, along with other tools, will allow for the climatic impact of BC over time to be evaluated in terms of changes in the geographical and sectoral distribution of emissions; it will also identify where additional mitigation measures can make a difference and at what cost. The work has been supported by the Clean Air Task Force (www.catf.us), a US-based NGO that has been working extensively in this area.

4.2 Black carbon

The significance of BC is higher in the Arctic than elsewhere because atmospheric absorption is enhanced by the high albedo of snow and ice surfaces (Quinn et al., 2008; AMAP, 2009). Furthermore, the albedo of snow and ice is reduced by BC deposition (e.g., Hansen & Nazarenko, 2004; Flanner et al., 2009). Therefore, reducing BC emissions may provide a means to slow down the Arctic warming and thus constrain the length of the melting season and reduce the feedback effects. BC is also a component of particulate matter, which is recognized as having adverse health effects. Consequently, the reductions would also bring about co-benefits for public health. Since BC is always emitted by other species as well (some of them, e.g., organic carbon aerosol (OC) or sulfur dioxide (SO_2) have been shown to cause cooling), the net-effect of all emitted species should be taken into account when assessing climate effects.

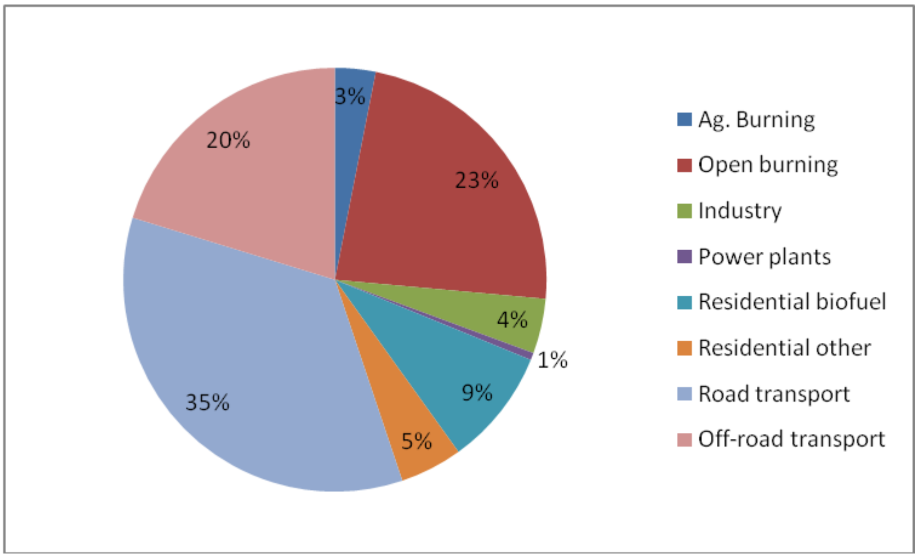
4.2.1 Important source sectors

Since BC is not well mixed globally, the main source sectors and regions of BC transported to the Arctic have to be studied and identified before developing any reasonable reduction strategies (Law & Stohl, 2007, Quinn et al., 2008). Recent research (e.g., Stohl, 2006; Hirdman et al., 2010) has shown that emissions from high-latitude Eurasia are important contributors to Arctic surface concentrations of BC. The Arctic surface concentrations are extremely sensitive to emissions within the Arctic (Hirdman et al., 2010) and possible changes in local source activities (e.g., shipping, oil and gas drilling) thus play an important role as well. The upper Arctic atmosphere is affected by emissions from northern Eurasia, as well as North America. The concentrations of BC are enhanced in the Arctic atmosphere during winter and spring when the transport of pollutants from lower latitudes is most efficient (Quinn et al., 2008); therefore, the seasonality of the emission should be taken into account when planning effective mitigation measures.

Black carbon is generated due to incomplete combustion of fossil fuels or biomass. Large global black carbon sources include diesel engines, domestic burning (e.g., cook stoves), biomass burning, and industrial sources (Bond et al., 2004). While some BC is produced in the Arctic itself, most pollution is transported from the eight Arctic Council nations and the near-Arctic regions (north of latitude 40), which includes much of the European Union, Russia, Ukraine, China (north of Beijing), Canada, and part of the United States. As illustrated in Figure 22 (based on the results of Bond et al., 2004), the use of diesel fuel, open burning (both agricultural burning and wildfires), and residential combustion of solid fuels account for most of the BC that reaches the Arctic (Sarofim et al., 2009).

What this figure does not show are emissions from explorations of oil and gas in the northern latitudes. However, estimates of BC (or any other pollutant) from this source are very uncertain and measurements on these sources have only recently been initiated. Preliminary estimates of the GAINS model indicate that emissions of BC from flaring might contribute up to 10% of the currently estimated BC total in the Arctic, originating primarily in Russia and the North Sea. The national emission structure varies from country to country (see Fig. 24 for Finland) and consequently, an abatement strategy may need to take these differences into account.

Figure 23 Contribution of primary sources by the Arctic nations to total BC emissions in 2000.



Quinn et al. (2008) assert that reducing black carbon concentrations requires targeting sources that emit aerosols with a high absorptivity and relatively low reflectance (e.g., diesel combustion and residential cook stoves). Effective mitigation to reduce within-Arctic emissions of black carbon may require implementing emission controls on maritime vessels operating within Arctic waters, especially since the shipping traffic is likely to increase if the sea ice extent and the snow/ice pack decrease (Quinn et al., 2008; IMO, 2010). Additional strategies include reducing the prescribed agricultural burning in Eastern Europe so that black carbon (as well as organic carbon) emission and deposition does not occur in spring when the transport of pollutants to the Arctic is heightened.

4.2.2 Finnish national emissions and emission scenarios

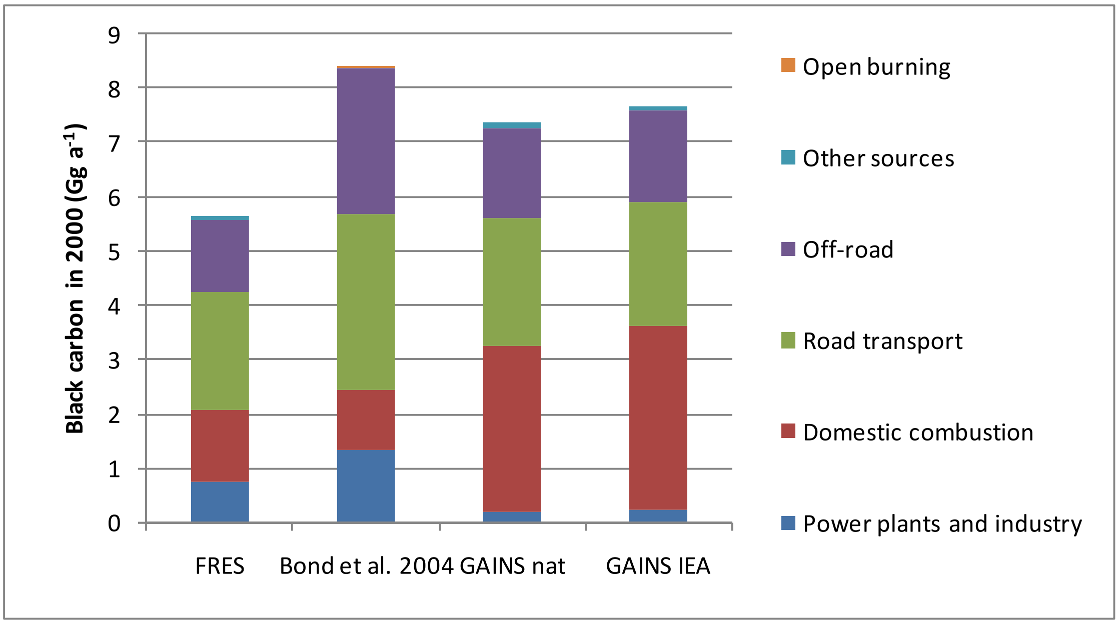
Estimates of BC emissions are fraught with significant uncertainties (e.g., Kupiainen & Klimont, 2007; Bond et al., 2004) owing to the lack of dedicated measurements that reflect on regional operating practices, fuels, and technologies, but also to poor activity data for some of the key sectors such as residential biofuel combustion. Figure 10 illustrates the Finnish national BC emissions by key sectors, estimated by various research groups for the year 2000. They vary by up to 30% at the national level, while the divergence is even greater at the sectoral level. The following datasets are presented:

- FRES' - estimate by the Finnish Regional Emission Scenario model (FRES) of the Finnish Environment Institute (Kupiainen & Karvosenoja, 2010);
- 'Bond' - the global inventory for 1996 (Bond et al., 2004) recently scaled to the year 2000 (Sarofim et al., 2009);

- 'GAINS' - IIASA's GAINS model (http://gains.iiasa.ac.at), which calculated two energy data sets – 'nat' based on the national Finish submission within the framework of the revision of the Gothenburg Protocol, and 'IEA' based on the International Energy Agency (IEA) database.

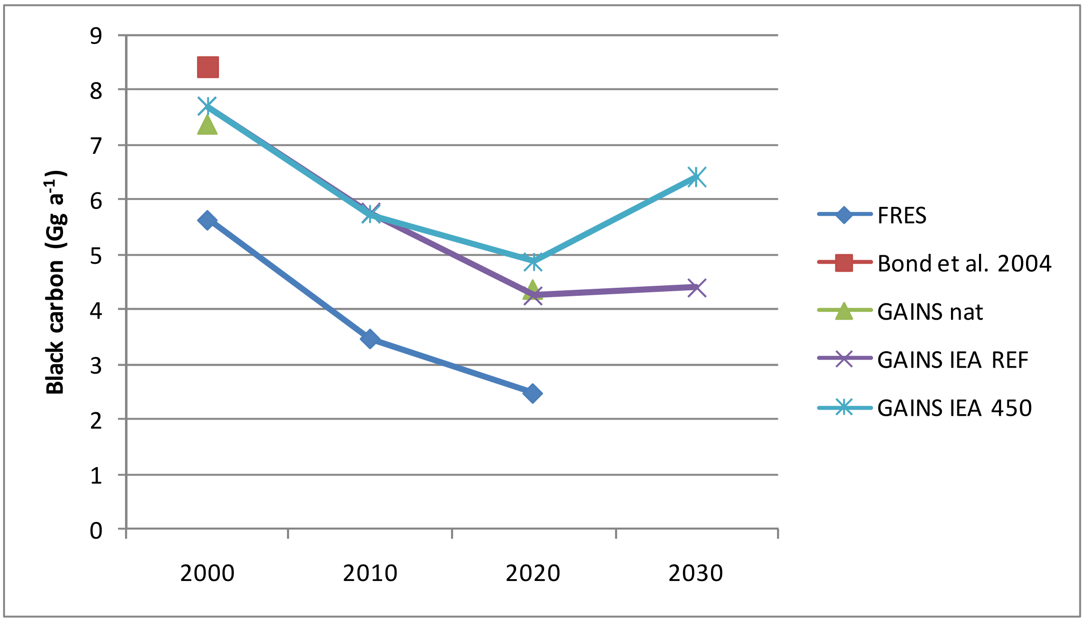
In general, all datasets demonstrate that traffic (road and off-road) and domestic combustion (primary wood burning) are the most important source sectors in Finland. However, Bond et al. (2004) estimate significantly higher emissions from transport than other research, owing to their assumption that a certain proportion of vehicles (about 5–10%) belong to the so-called 'high emitters' with emissions several times higher than vehicles that comply with the prescribed country-specific vehicle emission standards. GAINS, on the other hand, arrives at consistently higher estimates for domestic combustion and lower ones for industry. The primary reasons for the divergences in the domestic sector include – beyond emission factors – differences in fuel wood consumption, shares and detailed assumptions about the combustion technologies in place as well as their operation practices. The three teams providing the BC estimates illustrated in Figure 23 are collaborating on the harmonization of estimates for the Arctic nations under the Arctic Council Task Force on SLCF, the AMAP expert group on SLCF, and the Clean Air Task Force. The work is expected to be finalized by mid-2011.

Figure 24 Finnish BC emissions (Gg a^{-1}) by sector in 2000.



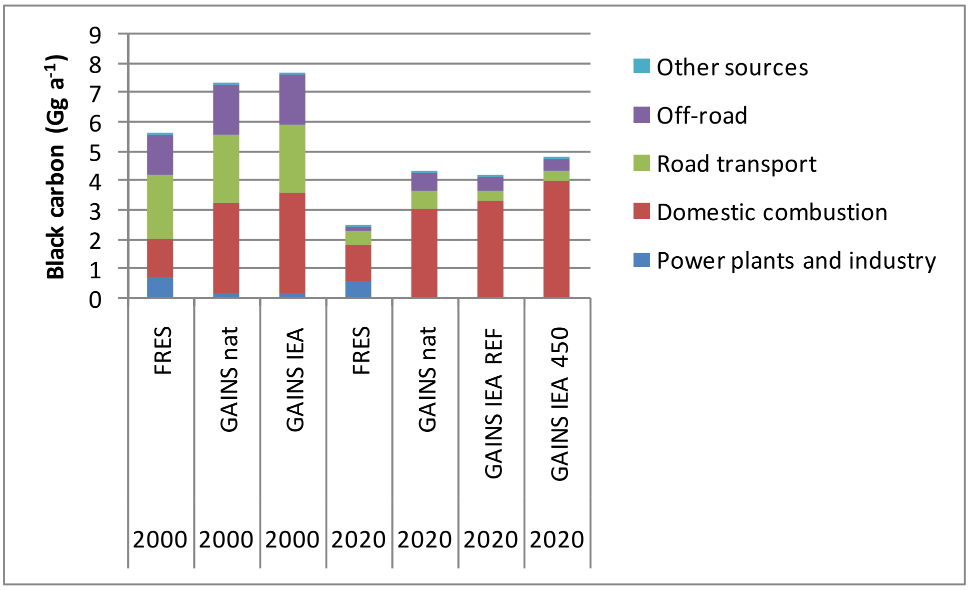
The next figure (Fig. 25) presents the expected changes in total BC emissions in Finland until 2030. Abstracting from the difference in the estimate for the base year, the trends up to 2020 are virtually the same in all projections. All of these scenarios assume successful implementation of the current policy targeting air pollutants, and not BC specifically. The 'FRES' projection for 2010 and 2020 originates from the 2005 national climate strategy WAM (With Additional Measures), while GAINS' IEA projections were developed on the basis of the IEA World Energy Outlook 2009 (IEA, 2009). The discrepancy between the 'REF'erence and the '450' scenario for the year 2030 is attributable to different assumptions on the future of Finland's energy system to meet the current goals of the national policy (REF) or to achieve a global stabilization of CO_2 concentrations at the level of 450 ppm. The '450' scenario is based on more biofuel use in the residential sector, among others, which leads to higher BC emissions (cf. Fig. 26). Consequently, the impact of CO_2 driven climate policies (GAINS IEA 450 vs. GAINS IEA REF) needs to be carefully evaluated, assuring that it also results in reduced climate forcing, since aerosols like BC and other co-emitted SLCF contribute to warming.

Figure 25 Expected evolution of BC emissions in Finland until 2030.



The comparison of sectoral emissions in Finland in 2000 and 2020 (Fig. 26) indicates that while it is expected that transport sector emissions will be reduced effectively, the role of domestic combustion will increase, and that emissions from this sector may actually rise in absolute terms. The contribution from transport sources is declining due to the increased share of vehicles with enhanced emission abatement (Euro-levels), which also leads to a significant reduction in BC emission rates. The scenarios presented assume improvements in the combustion technology used in the domestic sector (new and more efficient stoves, etc.), but their application is offset by the expected growth in fuel wood use, thus making this sector Finland's leading BC contributor in the future. However, close monitoring of whether the Euro-X technologies deliver the anticipated reductions in the future is necessary, as well as of the objective to limit the number of high emitting vehicles to a minimum by, e.g., the extension of maintenance and repair programs which might be of considerable significance for off-road machinery with its very long lifetimes.

Figure 26 Baseline (2000) and future (2020) estimates of sectoral BC emissions in Finland based on selected studies.



4.2.3 Abatement potential

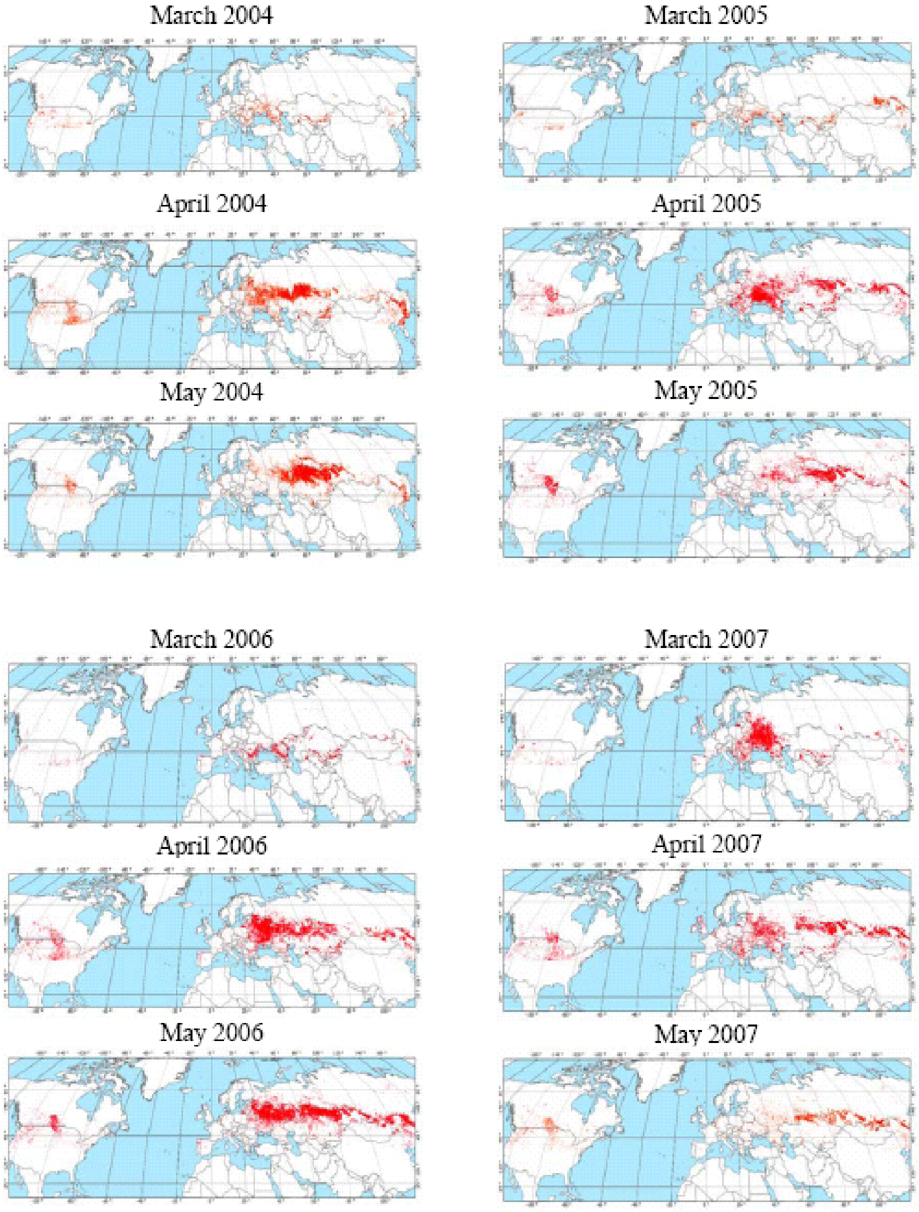
None of the existing laws specifically target the reduction of BC, although a number of policy initiatives have taken it into consideration (AC-SAO, 2009; UNECE, 2009; UNEP, 2009ab). However, since BC is co-emitted with several controlled pollutants, a reduction in emissions by several sectors is expected as demonstrated in the previous section for the current legislation scenario (CLE) for Finland.

Similarly, recent global BC projections estimate declining emissions in North America, Europe, and parts of the former Soviet Union block (Cofala et al., 2007; Streets et al., 2004). As already indicated in the preceding section, a reduction is not expected to come about in all sectors, and it is important to evaluate these changes in detail considering that location of the emissions and season plays a role from the arctic point of view (Quinn et al., 2008; see also next section). For example, emissions from northern areas are more likely transported over snow or ice-covered regions where they are also more likely to result in net warming (Sarofim et al., 2009).

Further reductions in BC could, for example, be achieved by introducing diesel retrofits (especially for off-road diesel machinery) and reducing or shifting the timing of open burning of crop residues, particularly in Eastern Europe and northern Asia. The latter factor is important because the burning of crop residue at present largely takes place in spring (cf. Fig. 26), when the emissions reach the Arctic. Furthermore, reductions in the domestic sector could be achieved by encouraging or enforcing the use of the best available combustion technology as soon as possible, although such strategies would only be effective at a later point owing to the long lifetime of the equipment in question. The latter strategy would not only reduce emission rates per unit of fuel, but would also lead to lower biofuel consumption. Last but not least, within and near-arctic sources, such as shipping and flaring in oil and gas production facilities, should be targeted.

The question regarding the possible importance of shipping emissions has been evaluated by Corbett et al (2010). Although Arctic shipping does not, in total, contribute a significant amount to the region's air emissions, including BC, the emission occurs far north and therefore has a stronger climate impact (Quinn et al., 2008). They are projected to rise together with increasing shipping activity owing to the decline in ice coverage (Arctic Council, 2009, Corbett et al., 2010). Corbett et al. (2010) estimated that BC emissions from Arctic shipping could rise up to 5 Gg a^{-1} (high growth, no control scenario). This is a major concern, because the order of magnitude is similar to, for example, emissions projected for the whole of Finland in 2020 (Fig. 26). Possible future shipping fuel quality regulations through the MARPOL Annex VI legislation, for example, on sulfur content, do not necessarily reduce BC emissions, albeit BC mitigation may benefit from it because some BC controls require lower sulfur fuels (Corbett et al., 2010). However, in order to asses the net radiative forcing of such a strategy, the impact on SO_2 emissions must be considered since they contribute to climate cooling.

Figure 27 Satellite images of agricultural burning fires in the Northern Hemisphere (Pettus, 2009). (Maps produced by Arthur Lembo, Assistant Professor of Geology and Geoscience at Salisbury University, using MODIS active fire and land use data).



March 2004

March 2005

April 2004

April 2005

May 2004

May 2005

March 2006

March 2007

April 2006

April 2007

May 2006

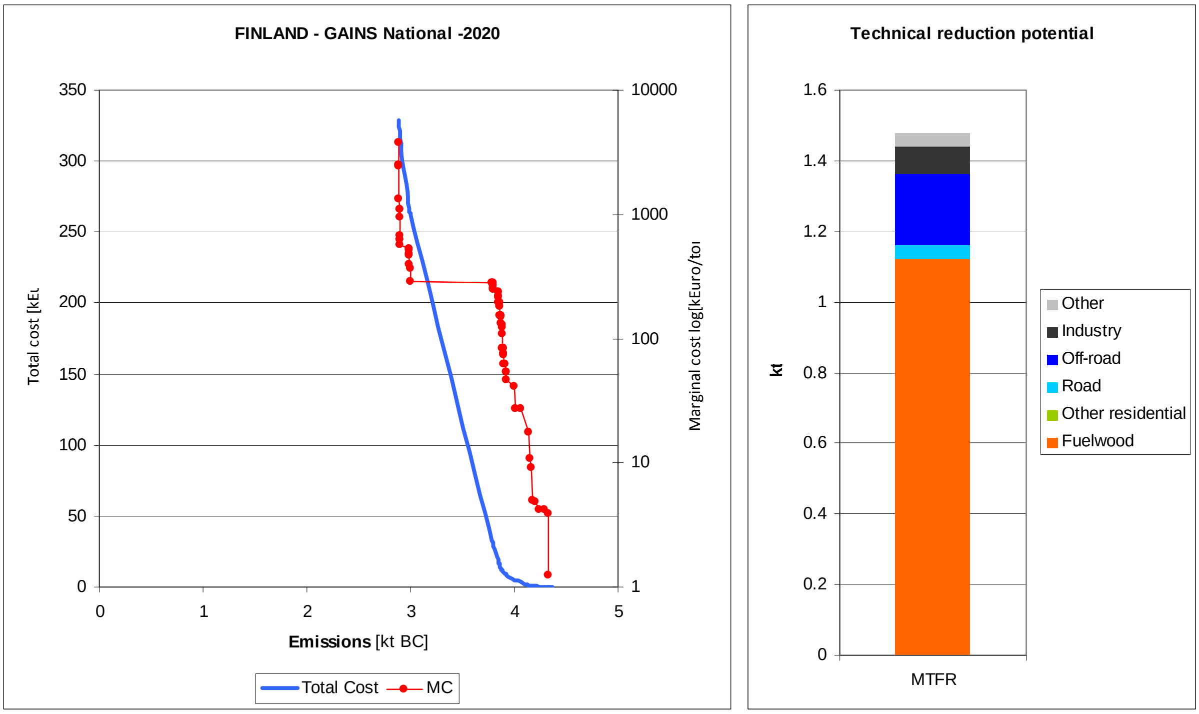
May 2007

A heated debate on geoengineering solutions to climate change is currently taking place. Proposed solutions also include options that focus on regional problems, like the disappearing Arctic Sea ice (Royal Society, 2009). For example, a technology that involves seeding clouds with sea salt to increase their brightness has been discussed within the Arctic context (Royal Society, 2009; Tollefson, 2010). The primary concerns with regard to the technology include the potential impact on rainfall patterns over down-wind land areas and the possible adverse effects of local cooling on winds and ocean currents (Royal Society, 2009). Geoengineering may provide interesting opportunities to mitigate climate change, but could also bear substantial risks in terms of adverse side-effects, and responsible approaches should therefore be studied carefully. A group of scientists intends to present a relevant research program to the Arctic Council for approval (Tollefson, 2010).

We have developed a preliminary assessment of BC abatement potential for 2020 for all Arctic nations under the umbrella of the Arctic Council TF on SLCF. This assessment was presented at the last meeting of the Task Force in San Francisco (10–12 February 2010) and respective data sets are being prepared for review by national experts. Here, a summary of Finland's abatement potential (Fig. 28) is presented, calculated for the GAINS national scenario. The key sector for which a reduction potential was identified is residential combustion (as discussed earlier); more specifically, about 80% of the reduction potential in the domestic sector is associated with fuel wood use in heating stoves, and the model assumes the introduction of improved stoves, as well as a restricted (up to 35%) replacement with pellet stoves. These assumptions need further verification which was initiated in the Arctic Council TF consultations. Not only reduction potentials, but also cost estimates of reduction measures need careful evaluation and must take national factors into account.

The next key sector in which a reduction in BC can be achieved is off-road machinery. The options rank lower on the cost curve (lower marginal costs), but do not represent a major mitigation potential. However, their age and geographical distribution is important and needs to be better understood to ensure that any future policy targeting these sources addresses the worst polluters.

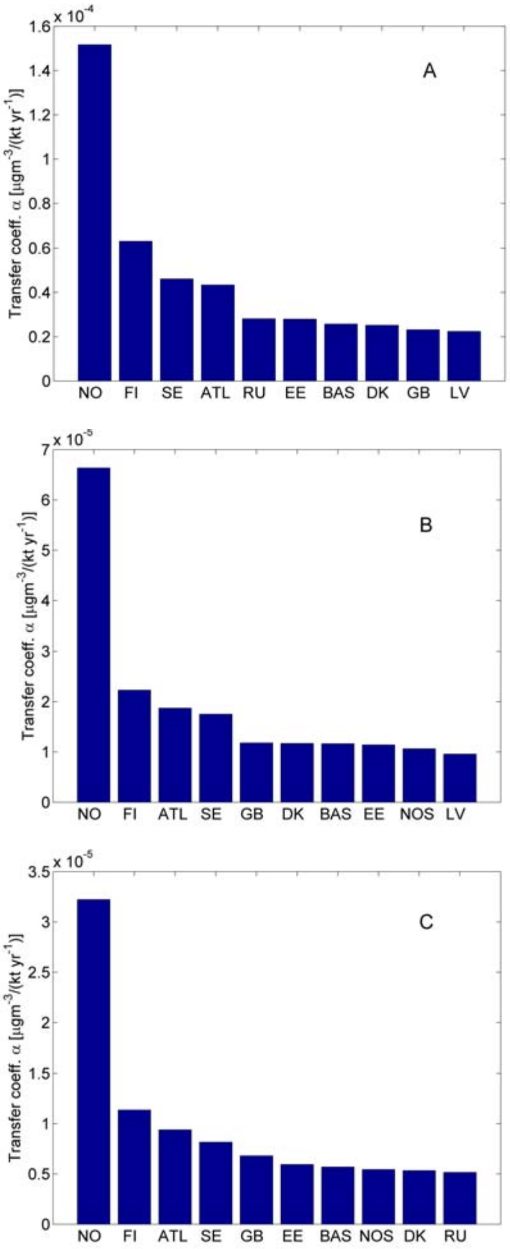
Figure 28 Preliminary cost curve and abatement potential of BC emissions for Finland in 2020 (GAINS model).



4.3 Particulate matter transport to the Arctic

Figure 29 illustrates the transfer coefficients for primary particulate matter from European source regions (including European Russia) to the Arctic, using three different definitions for the Arctic. A…north of 68°N, B…north of 72°N, and C…north of 75°N. These results are derived from the EMEP model calculations (Kiesewetter, 2009) and indicate that Arctic pollution levels are most sensitive to the northern-most European countries, with Norway ranking first before Finland and Sweden (Kiesewetter, 2009).

Figure 29 Transfer coefficients from European source regions to the Arctic, using three different definitions for the Arctic. A…north of 68°N, B…north of 72°N, C…north of 75°N.

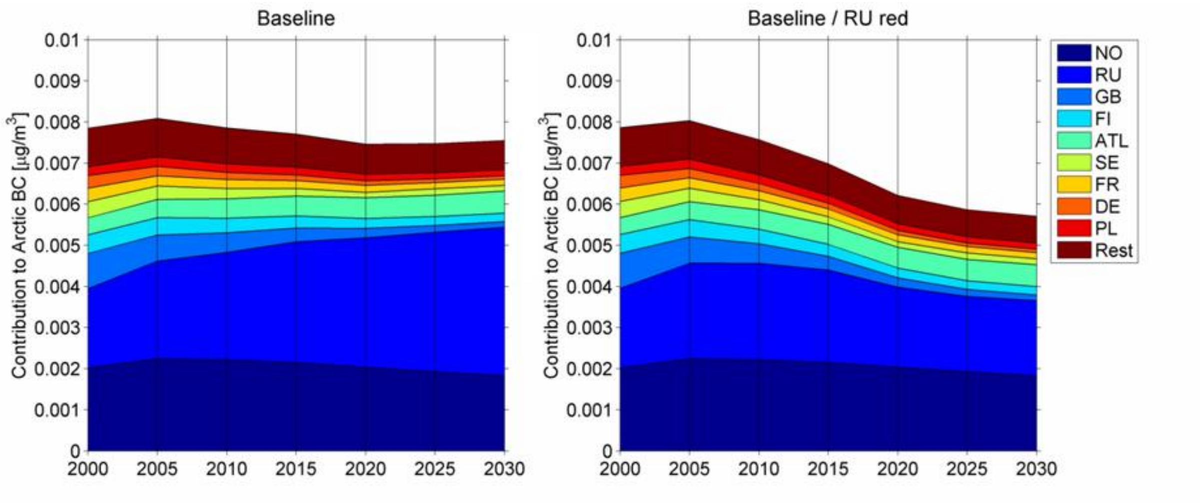


Abbreviations: Norway NO, Finland FI, Atlantic Ocean ATL, Sweden SE, Great Britain GB, Estonia EE, Baltic Sea BAS, North Sea NOs, Denmark DK, European Russia RU.

Source: Kiesewetter, 2009.

In order to estimate the actual impact on the Arctic, these coefficients should be further weighted by country-specific emissions. Figure 30 presents the country and sea area-specific contributions to Arctic BC concentration in 2000–2030 based on the CLE 2007 Baseline Scenario (left) and the CLE 2007 Baseline / RU red scenario (right) based on the IIASA GAINS model. The influence of Finnish emissions is estimated to be approximately the fourth largest.

Figure 30 Contributions to Arctic BC concentration based on the 'CLE 2007 Baseline' scenario (left) and the 'CLE 2007 Baseline/RU red' scenario (right).



"Rest" refers to the rest of Europe as considered in the EMEP model. In both scenarios, ship emissions from the RCP 8.5 scenario were added (showing up explicitly as Atlantic emissions, ATL).

Figure from Kiesewetter, 2009.

The analysis carried out by Kiesewetter (2009) relied on a dated set of data on emissions (CLE 2007 Baseline), which were developed around 2005. The most recent GAINS calculations reveal some significant changes in absolute BC emissions by the Arctic nations. The reasons for this include updated emission factors and activity data which, in some countries, notably Norway, lead to lower BC. However, this does not affect the finding on the relative significance of Arctic nations' emissions and we expect the level of importance to remain. We intend to update this analysis with new emission data in the near future.

4.4 Summary and concluding remarks

Reductions in the atmospheric burden of CO_2 shall form the basis of any meaningful effort to mitigate climate forcing. But even if swift and profound reductions are made, the rapid melting of the Arctic may not be delayed owing to the long lifetime of CO_2 in the atmosphere. However, there are shorter-lived climate forcing agents (SLCF) than CO_2, including black carbon aerosol (BC, commonly known as "soot"), tropospheric ozone, and methane (CH_4). Due to a shorter residence time in the atmosphere than CO_2, reductions in their concentrations could be felt much more quickly than the decrease in long-lived greenhouse gases (Quinn et al., 2008; Schindell & Faluvegi 2009; Klimont, 2009).

The significance of BC is higher in the Arctic than elsewhere, because atmospheric absorption is enhanced by the high albedo of snow and ice surfaces (Quinn et al., 2008; AMAP, 2009). In addition, the albedo of snow and ice is reduced by BC deposition (e.g., Hansen & Nazarenko, 2004; Flanner et al., 2009). Therefore, reducing BC emissions may provide a means to cool down the Arctic environment, to limit the length of the melting season, and reduce the feedback effects.

The use of diesel fuel, open burning (both agricultural burning and wildfires), and residential combustion of solid fuels account for the majority of BC that reaches the Arctic (Sarofim et al., 2009). Potentially large, but as of yet poorly quantified, emissions result from the exploration of oil and gas in the northern latitudes; Preliminary estimates by the GAINS model indicate that flaring could contribute up to 10% of the currently estimated total Arctic nations' BC emissions, originating primarily in Russia and the North Sea. Considering only Europe, Arctic pollution levels are most sensitive to the northern-most European countries, with Norway ranking first before Finland and Sweden (Kiesewetter, 2009).

The sectors with the highest BC emissions in Finland include transport (road and off-road) and domestic combustion (primarily, wood burning). It is expected that by 2020 transport sector emissions will have been effectively reduced due to an increased share of vehicles with enhanced emission abatement (Euro-levels). However, close monitoring of whether technology delivers the expected reductions in the future is necessary, as is the objective to limit the number of high emitting vehicles to a minimum by, e.g., extending maintenance and repair programs which could be of considerable significance for off-road machinery with its very long lifetimes. The scenarios presented anticipate improvements in the combustion technology used in the domestic sector (new and more efficient stoves, etc.), but their application will be offset by the expected growth in fuel wood use, making this sector Finland's highest BC contributor in the future.

A comparison of emissions from all Arctic Council nations reveals that Finland only contributes a few percent of total emissions that affect the Arctic and obviously cannot bring about significant reductions in emissions or forcing on its own. Consolidated international action, e.g., ongoing activities under the umbrella of the Arctic Council, is required.

The national emission structure will vary from country to country and consequently, a consolidated abatement strategy may need to take the differences into account. None of the existing laws specifically targets the reduction of BC, although it has been considered by a number of policy initiatives (AC-SAO, 2009; UNECE, 2009; UNEP, 2009ab). However, since BC is co-emitted with pollutants that are controlled by current legislation, a reduction in emissions by several sectors is expected in most of the Arctic countries, including Finland. This potentially removes the pressure from transport to control its emissions. However, the distribution of transport sources must be carefully evaluated, taking Arctic shipping and the use of off-road diesel machinery in the far north into account. The latter plays an important role since the typical lifetimes of off-road diesel engines are quite long and, therefore, additional retrofit and maintenance programs may have to be established to achieve the expected reductions.

5 INTERACTION WITH RUSSIA: ENERGY, FOREST SECTOR, ECOSYSTEMS AND ENVIRONMENT

5.1 Introduction

Huge natural resources are concentrated in Russian Arctic. Here is extracted about 80% of Russian gas, more 90% nickel and cobalt, 96% platinoides, 60% of copper etc. The mineable resources of carbohydrates on the Russian Arctic shelf comprise 100 billion ton of standard coal including 15.5 billion t of oil and 84.5 trillion m^3 of gas, or 20–25 world resources of carbohydrates (www.minregion.ru). About 35% of the total deposits of oil are in remote regions with extreme transport conditions.

The Finnish forest sector generates approximately 7% of the country's GDP. Wood processing, the pulp and paper industry play a key role in Finland's economy (approximately 18% of the volume of industrial output and more than one-third of its export output). On average, 70% of forest products and 90% of paper are exported from Finland to 140 countries. Finland is the second largest exporter of paper and cardboard in the world, and the fourth largest exporter of coniferous timber.

The industrial capacity of Finland's forest industry allows for the processing of approximately 65–70 million m^3 of round wood (75 million m^3 before the economic crises). Currently, 85-90% of required wood is supplied by the country's own forests and 10–15% is imported; 80% of the imported wood originates from Russia. Large forest industry companies purchase approximately 87% of required wood from external suppliers (61% from private Finnish owners and 26% from Russia). Russia exported 13.4 million m^3 of wood to Finland in 2006, and 11.1 million m^3 in 2007. Over 63% of the total volume is made up of deciduous wood, primarily birch wood for pulp production (in Finland, birch forests cover only 15% of the area). Thus, the impacts of climate change on both the Finnish and Russian forest sectors are of particular interest to understand the future of the supply of wood to the Finnish economy.

Finland's economic interest in Russian wood exports has an economic motive. Wood can be purchased relatively cheaper and wood imports decrease the price pressure of the national suppliers. According to information from the Russian Federal Customs Service, the average price for Russian industrial round wood (per 1 m^3) rose from $57.7 in 1995 to $83.9 per m^3 in 2007. Finnish forest industry companies have invested about 1 billion EUR in Russia over the last two decades.

Currently, Russia earns over 500 million EUR annually from timber exports to Finland. About half of the total amount of wood imported from Russia is pulpwood, for which there is only little market demand in Russia. The export of wood products secures around 40,000 jobs in the Russian forest sector (in addition to jobs in wood transport). Round wood is imported from northwestern Russia, mostly from Karelia Republic, Vologda and Novgorod oblasts.

According to several studies, the share of round wood in Russian wood exports was approx. 60% (51 million m^3 in 2006, of which around 85% was bought by the three leading pulp and paper manufacturers worldwide– China, Japan, and Finland), and 53.7 million m^3 in 2007 (for comparison, Canada exports approx. 2% industrial round wood, while Finland and Germany export 1.1%). In 2007, round wood exports comprised 47% of all of Russia's wood products export. These numbers do not include unaccounted (i.e., illegal) export, which is estimated at above 20% of the official trade and is especially high in the Russian Far East and North East.

Future needs for Russian wood imports to Finland will largely depend on the possibility of Finnish forests to increase the domestic harvest of wood. There are currently 52 cellulose, paper and board plants based in Finland. If the Finnish pulp and paper industry uses 90–95% of its current capacity, the consumption of wood would thus comprise 55–60 million m^3 of round wood annually. Despite effective developments in advanced technologies oriented toward the production of biofuel, biocomponents and biochemicals in the country, it is very likely that the consumption of round wood in Finland will not decrease over the next two-three decades.

Numerous national Finnish studies (e.g., project FINADAPT, http://www.ymparisto.fi/default.asp?contentid=227529&lan=en&clan=en) indicate that the expected climate change will generally be favorable for the Finnish environment, agriculture (e.g., Peltonen-Sainio et al., 2009a,b,c) and forest sector, due to the lengthening of the growing season and improvement of thermal and hydrological conditions. Scenario A2 presumes that the total physiologically active growing season temperature will increase by almost 500 degree-days by 2080.

With regard to the forests, a substantial improvement in their growing conditions is anticipated, which will accelerate their growth rate and productivity, particularly of deciduous tree species. Climate change and proper forest management could increase the amount of carbon in Finnish forests by 17–34% (Matala et al. 2009).

The negative consequences of expected climate change include the increasing damage of forests by insects and shifting of this problem further northward. This impact will likely not be too strong and could be offset by proper mitigation measures. A special feature of the northern forests could thus be diminished. Winter heat spells may provide unfavorable physiological effects, and the timber felling conditions might become more hazardous.

The increasing occurrence of extreme weather events (wind, snow, fire) poses several risks for forests. Forest fire is currently not a critical issue for Finland. However, the forest fire potential is expected to increase by the end of this century, especially in southern Finland (Kilpeläinen et al. 2009). The annual number of forest fire alarm days will likely increase about twice (96–160 days compared with the currently 60–100 days). The expected increase in the annual frequency of forest fires across the entire country will be approximately 20% higher by the end of this century, with the greatest increase occurring in the southernmost part of Finland, where six to nine fires will occur annually per 1000 km^2 (i.e., a 29% increase).

On the whole, Finnish forests will substantially increase their potential for supplying round wood. From other side, it's necessary take into account some forecasts which state the decrease by up to a third the pulp and paper industry production and by a fifth the wood processing production from 2007 to 2020 (Hetemäki & Hänninen 2009). However, it is very likely that the demand for Russian wood imports will remain at the current level and may even be increased due to (1) likely increase of areas of protective forests in Finland with a restricted regime of industrial harvest; (2) specifics of both forest ownership in Finland and the system of procurement of wood by the Finnish forest industry; (3) the need for wood from particular tree species, specifically deciduous; and (4) economic considerations assuming the development of the Russian forest sector and an increase in its capacity to deliver relatively inexpensive wood. Thus, we suppose that the Russian forest sector will continue to play an important role in the future supply of Finland with round wood.

5.2 Potential

Russia has vast forest resources – 797 million ha of forest and 84 billion m^3 of growing stock volume. The Annual Allowable Cut (AAC, the norm of sustainable harvest) is defined at 597 million m^3 (2008) of which 302 million m^3 are in European Russia and 295 million m^3 in Siberia and the Far Eastern Federal *Okrugs*. The AAC consists of 313 million m^3 of coniferous and 284 million m^3 of deciduous wood. The average increment of major forest forming species in Russia comprises about 1 billion m^3 of which approximately 380 million m^3 are in the European part.

The peak of Russia's harvest was in the mid-1980s (around 350 million m^3/year). Currently, Russia ranks third among countries whose harvest exceeds 150 million m^3/year (approx.180 million m^3/year of commercial wood over the last three years). The current AAC is estimated at around 24% for the entire country, 30–40% in European Russia, and 15–20% in Siberia and the Russian Far East. However, the AAC in Russia also includes substantial areas of forest that are not accessible due to underdeveloped infrastructure or because they are protected (according to different estimates, AAC applies to about 50% of the entire country).

From the Finnish perspective, the most important factors include forest, forest management and the forest industry of Russia's North-West (9 administrative regions of the North Western Federal *Okrug*). According to official statistics, 18.8 million m^3 of round wood was exported from the North-West in 2006, mostly to Scandinavian countries.

The forest resources of Russia's North-West are characterized by the following features:

- forests cover 52.3% of the region's total area (88 million ha with a growing stock of 10 billion m^3); an average increment of around140 million m^3; roughly 65% of the area is represented by forests which are available for industrial harvest; coniferous forests cover 76%, deciduous 24% of the area; mature and overmature stands encompass nearly half of the area;
- in recent years, the actual harvest in the region was 42–44 million m^3/year, including 84% of the final harvest, 7% thinning, and 9% other harvest); these numbers do not include illegal ("unaccounted") harvest (20–25%);
- AAC applies to 45% of all species and 60% of coniferous; the highest level applies to the Republic Karelia at 75%);
- the quality of forests has decreased over the last 50 years; over 50% of the forest have a relative stocking of 0.6–0.4, the yield of round wood for lumber decreased by 8–10%; deconcentration of industrially valuable stands is continuously decreasing;

- road density in the North-West is very low and varies from 1.2 km/1000 ha in the Komi Republic and 11.6/1000 ha in Pskov oblast'; the construction of new roads remains negligible;
- a substantial part of logging is provided by obsolete machinery and technology; labor productivity is very low (about 1/5 in the wood processing industry, 1/3 in the production of pulp and paper, and 2/3 in plywood production – compared with the level of Scandinavian countries); prime costs of harvested wood comes close to those of Finland;
- there is an evident lack of tradition in intensive management of forest resources; the governance of forests has declined significantly, particularly after the introduction of the new Forest Code (2006).

A number of Russian and Finnish analyses indicate that the available forest resources in the North suffice to provide a total harvest of 40–50 million m^3 in mature and overmature forests for the next 50 years. This amount could be substantially increased, if intensive forest management were introduced in Russia. The biological potential of intermediate harvest (thinning, different types of selective and gradual cutting) is enormous, at the level of about 200 million m^3/year in European Russia. The European Forestry Institute reported significantly higher reserves – at the level of 400 million m^3 (http://www.metla.fi/julkaisut/workingpapers/2009/mwp134.htm); however, this exceeds the gross growth of forests of European Russia – a recent estimate lies at approximately 380 million m^3/year. This resource is practically not being used at the moment.

Huge forest resources are also found in Privolzhsky, Ural and the Siberian Federal Okrugs. However, the possibility of extended use of these resources and their inclusion in international trade will depend on future developments in the national economy and transport infrastructure in Russia. A substantial increase in wood exports from Siberia will depend on the future state of the Arctic Sea Route.

5.3 Prospectus: Impacts of climate change

Despite substantial differences in modeling predictions of future climates, the main tendencies with regard to climate change impacts on the terrestrial ecosystems and on forests in the territory of Northern Eurasia, in particular, can be aggregated as following:

(1) geographical and landscape changes of areas suitable for the growth of certain plants, particularly tree species (shift or disappearance of some productive species);

(2) increase or decrease of stability, vitality, and productivity of agricultural and forest ecosystems; it is expected that the warming trend will support the productivity of agriculture and forests in major regions of Northern Eurasia (Sirotenko & Abashina, 2008);

(3) climatic models predict that bioclimatic potential for agriculture will substantially increase in European Russia, the Russian Far East and West Siberia. However, analyses of extreme climate events predict that the main food-producing regions in the south will experience an increase in the number of poor harvests – this number will double by 2020 and triple by 2070 (Alcamo et al., 2003);

(4) on the whole, the productivity of forests in the territories of the forest zone will likely increase, although there is doubt that the trend of recent decades (increase of around +0.5%/year) will continue;

(5) increasing summer aridity of the climate in southern and Asian continental regions will very likely provide mostly negative impacts on forest ecosystems;

(6) bioclimatic models predict considerable changes in vegetation cover by the end of this century, particularly in Siberia; according to some forecasts (which are based on the IPCC climatic predictions), the forest area of Central Siberia is predicted to shrink twofold ; the border between the forests and steppes would shift 10 degrees north of its current position; the steppe area in southern Siberia will increase by 30% with a twofold extension of desertified steppes (Tchebakova et al., 2003);

(7) a substantial rise in the instability of regional weather (increasing length of dry summer periods, intensity of precipitation during, etc.) will generate risks of droughts and floods, and negatively impact the productivity of terrestrial ecosystems;

(8) expected changes of the ecosystem's ecological functions (e.g., impacts on biogeochemical cycles and on biodiversity);

(9) increase or decrease in nutrient retention and turnover;

(10) changes in species' reproduction cycles, regularities of succession dynamics, and changes in environmental and social services (e.g., shifting values of the forest ecosystem as a tourist attraction); and

(11) the thawing of permafrost will generate diverse but clearly negative impacts on ecosystems.

The current realities of social and economic development of North Eurasia, which are accompanied by the destructive anthropogenic impacts on the environment and natural landscapes may substantially accelerate the negative consequences of climatic change. Siberian regions serve as a typical example. Siberia functions as a basic "storage room" of Russia's natural resources. Nearly 85% of Russian natural gas reserves are found in Siberia, as is over 90 and 75% of its coal and lignite, respectively, over 95% of its lead, approx. 90% molybdenum, platinum and platinoids, and about 80% of the country's diamonds, 75% gold, 70% nickel and copper; 50% of its tin and zinc, etc. (Korytnyi, 2009). The region also has vast resources of renewable energy. For instance, the capacity of the hydroelectric power stations of the Angara-Yenisey basin comprises half of the capacity of all hydroelectric power stations of Russia.

Current methods for industrial exploitation of the northern territories do not present an optimistic future with regard to the interactions of industry and environment in North Eurasia. The level of atmospheric pollution and soil contamination in major regions of intensive oil and gas extraction has exceeded all acceptable limits. The rate of contamination of some regions (West Siberia, north of Krasnoyarsk Kray) has been rising. The quality of river water, particularly in regions with maximal density of population, does not correspond to the norms of water use for drinking and fisheries.

Man-made impacts and changes are widespread in the high latitudes of Russia, particularly in its Asian part, in regions characterized by intensive extraction and exploration of fossil fuel (oil and gas) and the use of other natural resources (wood, metals, etc.). On the whole, over 30% of the explored reserves of Russian oil and about 60% of its natural gas are found in permafrost regions.

The current governance of natural resources (in particular, forests), and the control of the use of natural resources have fallen below a critical level (e.g., Musin, 2007). The impacts of toxic anthropogenic water contamination, the decline of the human immune system, increasing stresses, impacts of many negative social phenomena connected, among others, to the intensification of migration processes, with a high probability that the negative impacts of climatic change on the standards of the population's life and health will accelerate, as well as on the further economic and social developments. For example, in regions of West Siberia with active oil and gas companies (data from "Russian Federation", 2006): (1) annually, up to 35,000 of the oil pipelines used in northern regions for intensive oil and gas extraction break; (2) of the 35,000 pipelines, approx. 300 have officially registered oil spills with >10,000 t for each; (3) over 15% of the tundra surface has been destroyed; and (4) the physical destruction of natural landscapes has exceeded >30% of total areas of the territories of central and southern taiga. A substantial part of these accidents is caused by melting permafrost. In the territories of the Yamalo-Nenetsk autonomous Okrug (official regional report on State of Environment, 2004): (1) all rivers of the Ob'-Irtysh basin are categorized in the 5th and 6th class of water quality, i.e., "dirty" or "very dirty"; the concentration of the combination of *Fe, Mn*, oil products, etc. exceeds the maximum concentration of pollutants by several ten-folds; (2) the ecological state of environment causes 80% of disease in the region; (3) parasitic contamination of water and fish has substantially increased over the last decades; and (4) a clear destructive impact of industrial intervention on the life of indigenous nations is evident.

The utilization and use of oil casing-head gas is unsatisfactory. According to different estimates, between 15 to 25 billion m^3 of such gas is burnt in torches annually (Krukov & Tokarev, 2009). The Government Commission on Fuel and Energy Complex reported that the amount of extracted casing-head gas in 2007 comprised 61.2 billion m^3 of which 16.7 billion m^3 were burnt in torches.

A demonstrative example of the possible negative impacts of the destruction of permafrost is the break of the oil pipeline in the Usinsky district of the Komi Republic in 1994, when about 200.000 t of oil spilled (Erzev et al., 2000). The part of the pipeline that had broken crossed an area of discontinuous permafrost with a temperature close to 0°C, across the bogs which did not exist in the mid-1970s.

Natural disturbances will very likely impact terrestrial ecosystems in a visibly negative way. The warming over the last two decades has provided striking examples of the possible acceleration of disturbances in North Eurasia. According to satellite assessments, the annual area of vegetation fires in Asian Russia exceeded 10 million ha between 1997 and 2007. The areas of wild fire on forested land in 1998 comprised about 12 million ha in 1998 and 17 million ha in 2003. The amount of consumed fuel and severity of the fire were very high. Carbon emissions were estimated at 160–210 Tg C in 1998, and about 270 Tg C in 2003 (e.g., Kaiji et al., 2003).

The irreversible character of the changes in forest ecosystems and the transformation of historically stabilized ecological processes become evident following so-called *catastrophic fires* (Yefremov & Shvidenko, 2004). Such fires provide irreversible change to ecotopes (for the given period, over several hundred years), as well as long-term environmental impacts on natural landscapes as a whole, dramatically impact major biogeochemical cycles, and often cause "green desertification" over large territories. There is evidence that the frequency and severity of catastrophic forest fires in different regions of North Eurasia has increased 2–3-fold over the last decades. These fires have a dramatic impact on biodiversity (Kulikov, 1998). Climate change is a major reason for this, but a clear link exists between the increased magnitude of catastrophic fires and enhanced anthropogenic impacts.

In general, the long-term environmental consequences of catastrophic forest fires become apparent through: (1) a significant (up to several times) decrease in the biological productivity of forest lands due to the destruction of the indigenous ecotopes and replacement of indigenous vegetation formations; (2) the substantial decline in the industrial potential of forests for the period of around 100 years; (3) irreversible changes in the cryogenic regime of soils and rocks; (4) the change of the long-term amplitude of hydrothermal indicators beyond natural fluctuation; (5) changes of multi-year average hydrothermal and bio-chemical indicators of aquatic and sediment runoff, as well as of hydrological regimes and channel processes of water streams; (6) the accumulative impacts on atmospheric processes resulting in the acceleration of global climate change; (7) the promotion of large-scale outbreaks of insects and disease; (8) the irreversible loss of biodiversity, including rare and threatened flora and fauna species; (9) the long-distance transfer of pyrogenic products; and (10) the change of historical migration routes of migratory birds, ground, and water animals.

There is a clear statistical link between the deforestation of lands and the forest fire occurrence rate. On average, a 1% increase in the forest fire occurrence rate in the taiga regions will cause a 6–10% decrease in the percentage of forest cover. According to estimates, over the last 50 years, catastrophic or recurrent forest fires have increased the total area of deforested lands in Asian Russia by approx. 20 million ha. Such lands are comprised of up to 70% bogs, 15% grass-shrub lands, 10% open woodlands, and up to 5% of stone fields and stone outcrops (Sheingauz, 2001; Yefremov & Shvidenko, 2004). Fires of such magnitude should be considered pyrogenic disasters beyond a regional context, with century-long biotic, environmental, and socio-economic consequences.

Climate change is linked to the profound transformations of biotic processes. In particular, Khabarovsk Kray recently faced a severe outbreak of gypsy moss (*Limantria dispar*) on an area of some 8 million ha. There is evidence that this phenomenon is an after effect of the pyrogenic disaster of 1998. It is worth noting that the synergism of fire and biotic disturbances is typical for the whole of Northern Eurasia. The outbreak of Siberian moth (*Dendrolimus superans sibiricus*) impacted between 8 and 10 million hectares of larch stands in 2001–2002 in NE territories where such outbreaks had never before been observed (north of Zabaikale, Saha Republic).

On the whole, the risks for terrestrial ecosystems, agriculture and forestry initiated by climate change and anthropogenic activities could be described as: (1) negative processes linked to the destruction of permafrost, including the physical destruction of sites, thermokarst, solifluction; (2) loss of soil fertility due to water erosion, soil compaction, desertification, lack of nutrients, salinization, increasing water table and other changes in water regime, soil contamination; (3) impoverishment of soil biota, decline in productivity of lands; (4) lack of water resources in arid regions; (5) damage of agricultural lands in river valleys due to an increase in inundation; (6) anomalous outbreaks and spatial distribution of traditional and new insects and microorganisms; (7) alteration of the forest fire regime; (8) loss of biodiversity; (9) "green" desertification, and (10) impacts of air pollution, soil and water contamination.

Permafrost degradation. Modeling studies on permafrost behavior in the 21st century predict a substantial decrease in the total area of permafrost; the area of continuous permafrost will likely decrease by 25–50% by 2080 (Anisimov & Beloluzkaya, 2003). Intensive development of thermokarst, gully formation, landslides, solifluction, floods, paludification (or aridity, depending on geographic distribution and landscape peculiarities, with northern steppization and "green desertification") is expected for large areas, especially for continuing ice-rich grounds (which cover about 35% of Yakutia and 35–40% of north-eastern Russia). According to predictions made by the Permafrost Institute in Yakutsk, lake and swamp cover may increase (by 1.3–3 times in a scenario of future moderate warming by +3 C) is non-uniform in different regions of Asian Russia. If the observed warming trend $\Delta t_0 \geq 0.06$ C yr^{-1} continues, unprecedented changes in the geocryological, landscape and ecological conditions are very likely in high latitudes of Northern Eurasia.

Permafrost and the wetlands of Northern Eurasia contain a huge amount of carbon: Available estimates range from 400 to 900 Pg C. The organic carbon of permafrost sediments varied between 0.6% and 4.9% and was characterized by an increasing humification index with permafrost depth, and a high CH_4 concentration was found in the top 4 m layer (Wagner et al., 2007). Warming may trigger dangerous acceleration of major biogeochemical cycles at the expense of a thermal increase in carbon emissions (as CO_2, CO, and CH_4). Hydrates of the Northern Seas are a second potentially large source of greenhouse gases.

Impoverishment of fragile (pseudo-equilibrium) ecosystems of high latitudes. A number of ecosystems, particularly of northern latitudinal and altitudinal ecotones, are facing a specific threat from global change. Degradation of cryoxerogenic landscapes of high latitude in Asian Russia could serve as an example. These landscapes suffer from salinization, an increase in alkalinity, water, wind, and thermokarst erosion. Today, 40% of hay fields in Yakutia suffer from surplus salinity and 50% of pasture has undergone digression of different extent. It is very likely that the specifics of on-going and expected climate change will accelerate these processes.

Acceleration of natural disturbances. It is also very likely that predicted climate change will provoke a dramatic increase in the extent, severity, and frequency of vegetation fire and insect outbreaks. A combined impact of fire and other anthropogenic and natural disturbances will accelerate the process of green desertification (current estimates are that 1 to 2 million ha per year have been lost to green desertification over the last decades). There is a threat of catastrophic fire seasons; over the last decade, such catastrophic fire seasons occurred in 1998 and 2003. Global experience shows that even countries that are very advanced in forest fire protection are not able to provide the satisfactory extinguishing of forest fires in the catastrophic years.

Risks for coastal areas and marine ecosystems. The increasing sea level and flooding of coastal areas, the change in the salinity regime of low reaches of rivers, the change in ecological processes in deltas, and the substantial intensification of processes of coastal erosion will negatively impact coastal and delta ecosystems. The rate of acceleration of decreasing sea ice and the shrinking ice cover of the Arctic Seas has already impacted the northern animal population.

Changing the hydrological regime. Risks triggered by the change in the hydrological regime are region-specific. The transformation of the hydrological cycle including a change in runoff of large Siberian rivers will impact the condition and dynamics of the vast wetland territories of West Siberia and those north of the region. The decrease in water table in permafrost area in combination with the acceleration of the fire regimes will provoke processes of northern steppization and green desertification. A steady deficit of water resources will cause yield loss of agricultural crops and pastures in southern regions.

Acceleration of emissions of greenhouse gases. Warming and direct and indirect anthropogenic impacts on natural landscape could lead to a substantial increase in emissions of greenhouse gases (mostly CO_2 and CH_4). Currently, even if the significant increase in disturbances is taken into account, terrestrial ecosystems of Siberia continue to serve as a net carbon sink at a level of 20–40 g C m^{-2} $year^{-1}$. However, it remains unclear to what extent the warming of permafrost areas has affected the budgets of greenhouse gases during the last decade.

Ecosystems and human health. It is very likely that climatic changes will impact human health and living conditions in a visibly negative way, both directly and indirectly, through changes in the ecosystem. The direct impact includes increasing severity and frequency of extreme climatic phenomena, such as flooding, increasing wind, and – in southern parts of the region – a rise in the number of hot days, heat waves, and longer and more intensive dry periods. Additionally, warming increases the danger of infectious diseases, particularly those which are spread by insect-carriers or by water. Severe intensification of epidemic processes caused by intestinal infection in the south (sometimes up to unprecedented levels), increasing parasitic and non-infection pathology, and an evident northward shifting of the areas of carriers of infection, are already being observed in different regions of Siberia. Likewise, negative impacts of global change on the region’s ecosystems (particularly agriculture and forest) will impact the well-being and standards of life of the local population.

5.4 Adaptation, mitigation, and ecological safety

The development and implementation of a preventive strategy of adaptation of landscapes and ecosystems to, and mitigation of, the negative consequences of global change could minimize the above-mentioned challenges and risks. The technical aspects of this process are well-known (e.g., IPCC, 2007). It includes relevant forms of management practices: Afforestation and deforestation, biofuel plantations and substitution through wood products, reduction of emissions from deforestation, improvement of forest management, and forest restoration within a degraded forest land (e.g., Robledo et al., 2008).

However, these and other activities are closely tied to the overall problem of sustainable management of natural resources in Russia, economic and social development of the territory, and ecological safety of the population. In essence, climate change should become one of the cornerstones of regional strategies for social and economic developments with inherently implemented global issues and links, building, *inter alia*, on the following major issues:

- development of a concept of sustainable development for regions in high latitudes; such a concept should be based on a unified policy of ecological safety for all boreal and polar regions under the expected climatic, social, and economic changes; an important initial stage of transition to sustainable development is a system of activities which would allow to overcome the current ecological and nature management crises;
- development of integrated observation systems over the entire circumpolar boreal biomes as an information base for integrated land use management under global change; these systems should provide early warnings of changes in the functioning Earth system and help recognize undesirable "surprises" in a timely manner, particularly in hot spot regions, e.g., permafrost regions; integration of ground observation (monitoring stations), multi-sensor remote sensing techniques and relevant ecological models is a cornerstone of such systems;
- based on the global change challenges, reconsideration of existing and introduction of a new, relevant system of specially protected territories around the polar circle with ecologically relevant regimes of nature management;
- taking into account that the forest in northern regions is a major stabilizing element of natural landscapes; the forest management paradigm requires substantial reconsideration – from a pure resource to a multi-service use of forests with a clear emphasis on environmental and protective services. It further requires a proper quantification of the "global utility" of forests, which would allow an understanding of the real value of forests in the contemporary world;
- development of a new strategy, establishing a legislative and institutional background of forest fire protection; such a strategy should include the relevant preparation of boreal landscapes for the expected climatic change;
- the problem of the interaction between humanity and nature in northern regions requires new ways of thinking and, in principle, new solutions for many issues – education, institutions, capacity-building, development and introduction of ecologically-friendly methods, machinery and technologies of industrial development in the northern territories;
- the development of a legislative and normative base of adaptation and mitigation is an urgent issue at both the federal and regional levels; in this regard, the situation of the post-Kyoto implementation in the region is clearly unsatisfactory;
- an as comprehensive as possible adoption of the Kyoto ideology/ mechanisms in different aspects (for obtaining heat and energy through modern technologies; full introduction of the biosphere in the post-Kyoto international process, etc.);
- the management of major biogeochemical cycles (basically, carbon and nitrogen) should be considered as an inherent part of sustainable land use management (including agriculture, forestry, wetland management).

However, all of the above-mentioned problems have not been properly considered in Russia, and, at best, remain a topic of discussion among politicians. A transition to sustainable development requires significant investments and political decisions. However, there are a lot of unresolved political, economic and social problems in Russia. The current system of taxation has nothing in common with actual rental taxation (Nagaeva, 2009). The development of strategies for environmental protection is an essential component of any decent state policy. The lack of such a strategy in Russia in addition to the absence of a special government body responsible for implementing such a strategy, is one of the key reasons for the permanent deterioration of environment in Russia and the increasing negative impacts on it (Pryazhinskaya, 2009). The continuation of these tendencies has lead to an aggravation of the degradation of terrestrial and water systems, and has generated numerous undesirable consequences and risks.

Russia faces substantial social and demographic problems. The population of the high latitude regions (including the European northern regions) has dramatically decreased during the last 20 years. The impoverishment of cultural and ethical norms is evident. The index of the development of human potential in the major boreal and polar regions in Russia has been consistently decreasing over the last decades (Mekush & Mekush, 2009).

Land use – land cover change (LULCC) in the region was during the last decades mostly driven by economic processes and inherited behavior of destruction of natural resources systems. This is revealed by the impoverishment of forests and their decreasing quality over large areas (decreasing areas of valuable coniferous forests; restoration of forests through change of species; increasing area of burnt areas and dead stands, etc.), particularly in densely populated areas. On the other hand, the restoration potential of boreal forests remains very high; this has resulted in the restoration of disturbed areas and an encroachment of forests and shrubs in previously non-forest areas. Another typical feature of LUCC is the abandonment of agricultural land in the forest steppe and steppe zones of the region. Such lands are not included in any management activities and these territories are now transforming into weed- and disease-breeders.

Decreasing the risks involved requires substantial improvements in available information. There is a lack of connections between economic development and impacts on the environment and spending of the natural capital. Traditional macroeconomic indicators reported for Russia do not account for the negative impacts of industry on the environment (Zabelina & Trynkona, 2009). There is evidently a need for the transition to an ecologically-corrected GDP. This would require the introduction of advanced systems of coupled ecological and economic accounting (like NAMEA, SEEA).

The future state of the environment and forest ecosystems in the Russian north, their impacts on the potential delivery of energy sources and wood from vast high latitude regions for domestic and international consumption will depend on the proper solution of the problems indicated above.

5.5 Political and socioeconomic development

Future Russian policies toward western countries are difficult to predict. In 2007, Russia announced an unprecedented regulation of the export of wood products, thereby introducing a mechanism of gradually increasing export duties. It was assumed that such a measure would support wood processing in the country. From 2006 to 2008, the Russian Government took a number of decisions that introduced tough regulations on the export of round wood, but later postponed the introduction of custom fees for round wood exports. Initially, export fees were increased: 20% of the custom value of the wood, but not less than 10 EUR per $m^3$was effective as of July 2007; in April 2008, 25%, but not less than 15 EUR per m^3 was introduced, and, finally, the intention was to raise the export fee to 80%, but not less than 50 EUR per m^3 (as of January 2009) However, the Russian Government has been forced to postpone the latest increase in custom fees to 2010 and 2011. Russian Prime Minister Putin stated at a meeting with the Finnish Prime Minister (in October 2009) that Russia would expand duty-free delivery of wood to Finland, particularly of deciduous wood for which there is no demand in Russia.

This customs policy (together with the global economic crises) has affected exports of Russian wood to Finland. In the structure of export receipts, the share of round wood after 2000 made up about one third of all exports while the share of the pulp and paper industry was less than 40%. This proportion has changed over the last years (e.g., in 2009, export of timber comprised 30.5% and round wood 55.4% of all exports). On the whole, Russian export of round wood decreased by 43.7% in 2009 compared with 2008.

The losses caused by such a policy are evident for both countries. Finland needs around 10 million m^3 of deciduous wood annually from Russia in order for its pulp and paper industry to work effectively. However, increasing Russian custom fees prevent a further development of round wood export.

Russian experts do not expect to achieve substantial success from this policy because of (1) the low capacity of the domestic market attributable to the absence of solvent demand (poverty of population), and (2) low competitive ability of end products (lack of modernization of the processing industry). These deficiencies are characteristic for Russia's entire economy, which basically remains afloat through its exports of raw materials and semi-processed goods. However, it is expected that export of round wood from Russia will decrease. If a new policy is introduced, Russian wood will lose its price competitive ability.

According to expert opinions, Russia will remain a raw-material appendage of Europe and particularly Finland until at least 2015–2020. On average, Russia has 1.2 km of roads per 1000 ha (that is 35 times less than in Finland), and 20–22 km/ 1000 ha in the fairly dense taiga regions. Expert calculations suggest that 3,000 km of roads with a hard surface need to be paved to provide effective transport to and from Russia's forests. This would require investments in the range of 18 billion rubles annually (with the average cost of 1km road at 6 million rubles (approx.$200.000). Based on estimates of the Russian Government, 12.500 km of forest roads need to urgently be constructed. Currently, about 200–300 km of roads are constructed annually.

Numerous decisions on improvements of Russia's forest sector (e.g., *Concept of Strategy of Development of the Forest Industry Sector of the Russian Federation by 2020*) are only materializing very slowly, and there is doubt that, e.g., the planned level of wood harvest of 297 million m3/year will actually be reached by 2020. It is impossible to realize investment projects aimed at the development and modernization of the forest industry within a short time. Some Russian experts claim that over the next decades, Russia will inevitably have to maintain its role as a global exporter of round wood. Some estimates assert that investments of around 2 billion US dollars annually over the next 30 years are required to raise the Russian forest industry to the level of developed European countries. The current level of investments in the Russian forest industry is very low, and this is not only a consequence of the economic crisis, but primarily attributable to the high level of risks and lack of stability, as well as the high level of criminalization and corruption in the country.

There still is little evidence of substantial future progress in the modernization of the Russian forest sector. This would require profound reforms of the state’s economic policy, tax regulation, and serious institutional changes.

6 GLOBAL LONG-TERM SCENARIOS OF ENERGY AND CLIMATE CHANGE MITIGATION-IMPLICATIONS FOR TECHNOLOGY, TRADE AND POLICY

Long-term scenarios are an indispensable tool for the assessment of major uncertainties, as well as of the consequences of alternative policy actions for global challenges. A number of global and regional scenario exercises have been conducted that focus on scenarios in terms of alternative socioeconomic development pathways and the subsequent impact of these scenarios on energy structures and environmental (including climatic) impacts (e.g., IPCC, 2007, WEO, 2007, etc.). This has also become increasingly relevant given the rising global concerns on preventing the impacts of dangerous climate change and the need for scenario-based quantification of the implications of low climate stabilization, for energy systems, as well as the impacts on climate change.

In this section of the report, we focus on two global scenarios with alternative socioeconomic dimensions and examine the development of energy systems in the future, along with the associated environmental consequences. We also discuss the need and implications of achieving climate stabilization at low levels, in particular through investments into energy systems, and the co-benefits for air pollution. While the scenarios are global in nature, we attempt to draw specific conclusions with respect to issues of importance within the Arctic and Finnish context-in particular energy resources, trade, technology and emissions.

We use a set of long-term scenarios developed at IIASA as a starting point (Riahi et al., 2007). These scenarios are a subset of the scenarios developed for the IPCC Special Report on Emissions Scenarios (SRES) (IPCC 2001), which were also used for a subsequent analysis of the feasibility of meeting a range of climate stabilization targets analyzed in the IPCC Third Assessment Report (TAR) (IPCC 2003), as well as within the Energy Modeling Forum (EMF) (Rao et al., 2004). These scenarios have undergone major numerical revisions in terms of socioeconomic assumptions (as detailed in Riahi et al., 2007). In addition, the scenarios encompass a multi-sector and multi-GHG perspective in which the integrated assessment paradigm is extended from the traditional focus on the energy sector to all other salient sectors (in particular agriculture and forestry) that emit GHGs or potentially contribute to climate change mitigation efforts through either emissions reductions or enhancements of GHG sinks. By a full coupling of the corresponding models that represent the energy, agriculture, and forestry sectors, we are not only able to consistently account for all GHGs and their respective mitigation potentials across the sectors[2], but for important feedbacks and interdependencies (e.g., competition for land use) between sectors as well. The scenarios also incorporate previously unexplored mitigation options, such as the use of biomass in conjunction with carbon sequestration and storage (CSS), which could result in an artificial 'sink' for anthropogenic CO_2 emissions in addition to traditionally considered forest sinks. These scenarios were used to explore a number of climate stabilization targets to determine the feasibility and costs of meeting alternative climate stabilization targets under a range of salient long-term uncertainties[2].

---

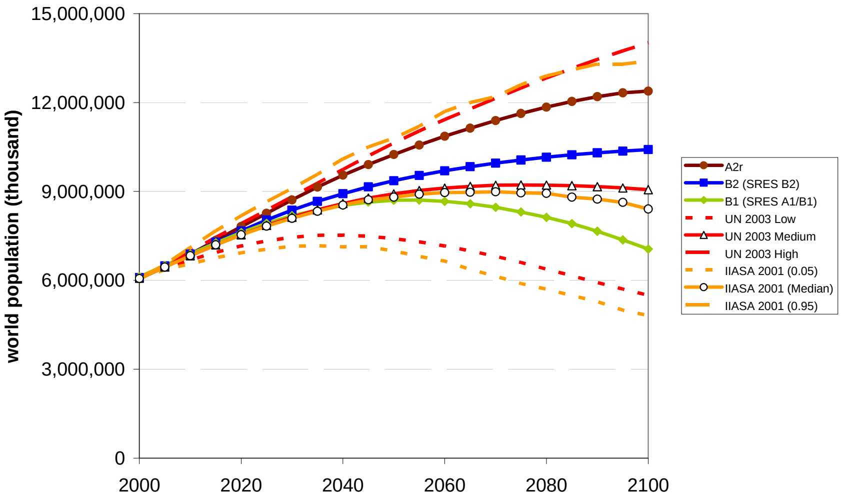
[2] We also include additional low climate stabilization levels here in addition to those discussed in Riahi et al., 2007

To meet this objective, we have developed two contrasting scenarios, A2r and B1, that aim to *bracket the upper and lower quadrants of emissions* and hence the extent of both climate change and of the potential *vulnerability to climate change*. The following sections describe the socio-economic drivers of these scenarios and the resulting impacts on eneryg systems and greenhouse gas emissions in the future.

6.1 Socioeconomic assumptions/impacts in current global energy-climate scenarios

An important distinguishing feature of these future scenarios is the assumptions on long-term demographic and economic growth. In B1, a rapid demographic transition from high to low fertility leads to a low total population projection. This, combined with the assumed high levels of education and free access to knowledge, capital, and technology, enables developing countries in particular to make full use of their demographic opportunity window. Rates of economic growth accelerate with the progress of demographic transition and are assumed to peak at the demographic opportunity window (maximum of the second derivative of population growth). In turn, accelerated rates of modernization, as reflected in economic development catch-up, also feed back into demographic development, which maintains the rapid mortality and fertility transitions characteristic of the B1 scenario. Conversely, scenario A2r assumes a delayed demographic transition which leads not only to a high population projection, but also to a delay in the potential to fully use the demographic opportunity window for development catch-up. Global population increases from approximately 6 billion in 2000 to around 9 billion by 2050 (8.7 and 9.3 billion in B1 and B2, respectively) and 7 (B1) billion by 2100. The A2r scenario is characterized by an assumed delay in demographic transition by some two to three decades, which leads to a world population of approximately 10 billion by 2050 and 12.4 billion by 2100. A comparison of the world population scenarios reported here with the original SRES study and the most recent population projections from IIASA and the UN is illustrated in Figure 31.

Figure 31 World population, comparison of different scenarios.



Reproduced from the Special Issue on Technological Change and Forecasting, 2007.

In terms of economic growth, the scenarios describe a world that is becoming more affluent, albeit at different rates and with different regional patterns. Global economic output (GEO) is estimated at USD 27 trillion (1990) at market exchange rates (MERs) in the year 2000. By 2050, GEO ranges between USD 106 (A2r) to 150 (B1) trillion. By 2100, the corresponding scenario range lies between USD 204 (A2r) and 392 (B1) trillion, which signifies an increase of a factor ranging from 7 to 14 over a period of 100 years. However, despite the overall economic growth, the distribution of this growth varies significantly by scenario, with a more uneven distribution in the A2r scenario than in the prosperous B1 scenario (for further details on the methodology used for downscaling, please see Gruebler et al., 2007).

Figure 32a World GDP (Market Exchange Rate), 2100, A2r.

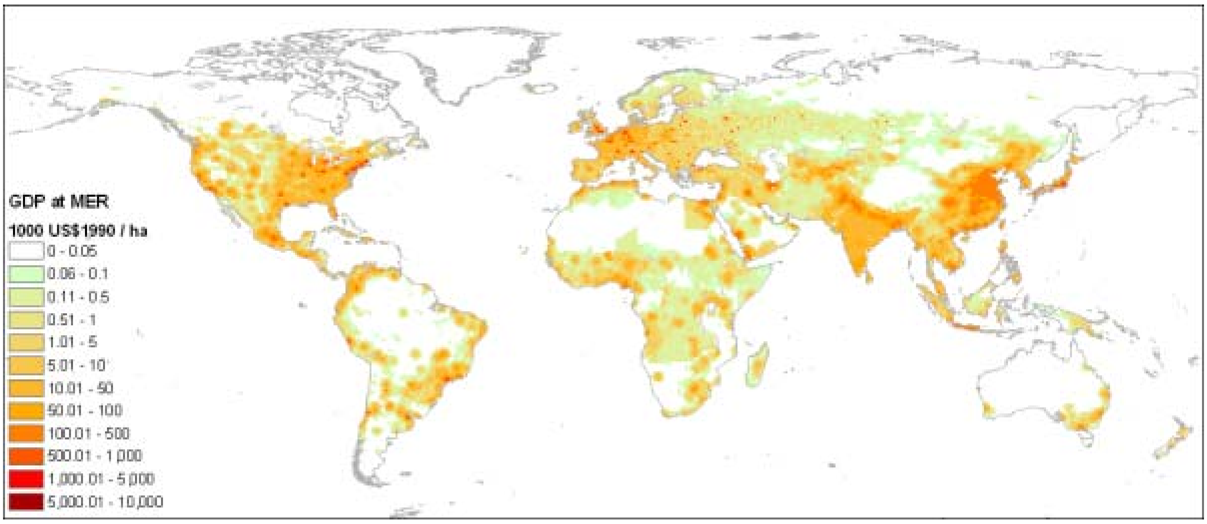
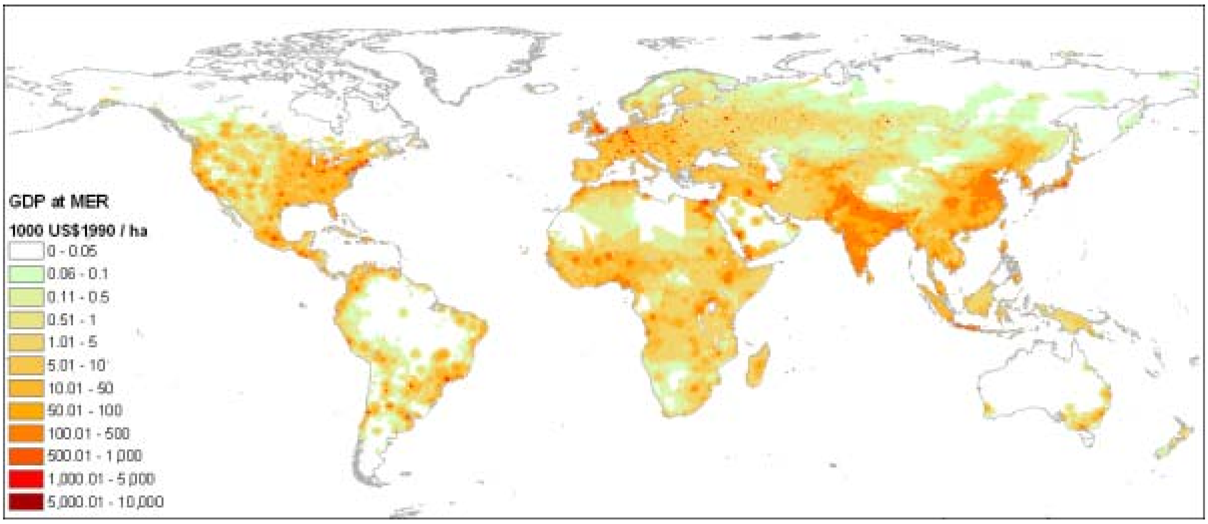


Figure 32b World GDP (Market Exchange Rate), 2100, B1.



The socioeconomic developments presented here can be expected to have significant impacts on future global energy use in terms of both the demand for energy, as well as the rates of technology deployment, especially of advanced technologies. This is particularly relevant for energy exporting regions like the Former Soviet Union (FSU), which is currently looking to expand its gas exports, as well as the number of energy importers Finland which will face increasing competition for resources in the future as developing countries like China look to increase their energy imports. The following section examines these impacts in more detail.

6.2 Future energy and environment implications

Global energy use in the scenarios is projected to increase two to four-fold over the century, depending on differences in energy efficiencies and technological change. Developing countries are expected to consume 60–70% of the energy demand during this century, thus putting enormous pressure on energy resources. The two scenarios illustrate contrasting trends with regard to fossil and non-fossil energy use as presented in Table 12, with the A2r scenario depicting a mostly fossil-dependent future while the B1 scenario expects a shift to non-fossil energy. These scenario characteristics are discussed in more detail below.

Table 12 Scenario characteristics.

	2000	A2r	B1
Demand (FE), EJ	290	1250	800
Technological change	-	Low	High
Energy Intensity Impr., %/year	-0.7*	-0.6	-1.7
Carbon Intensity Impr., %/year	-0.3*	-0.3	-1.5
Fossil energy (PE), EJ	340	1180	340
Non-fossil energy (PE), EJ	95	1080	1160
Emissions (Energy), GtC	7	27	6

*Historical development since 1850

An important assumption in both scenarios is the availability of fossil resources. Fossil fuel resource availability is differentiated by major fuel (coal, oil, and gas) as well as by resource category (especially conventional versus unconventional resources). Resource estimates of oil and gas as depicted in Table 13 include currently known reserves, as well as hitherto undiscovered ones. Current studies maintain that there are vast undiscovered potential resources in the Arctic region, for example (USGS, 2008). According to those estimates, the mean of the undiscovered gas resources of 25 Arctic provinces is about 46 tcm (excluding NGLs). However, as seen in Table 13, while these additional resources are significant, the large potential of unconventional gas resources already included in the scenarios, would imply that if production costs linked to Arctic gas were to decrease significantly in the future, this would mean a possible displacement of some of the existing unconventional gas' potential, but not necessary affect the implications of the scenarios. For example, studies that include the possibility of methane hydrates indicate that they represent a potentially vast fossil fuel energy source that could provide up to 10 or 15% of global natural gas production within the next two decades (Krey et al., 2009). Thus, resource availability does not appear to be a constraining factor, even in the longer term, but the economics of oil and gas extraction and technological advancements will play a key role with regard to continued investments in this sector.

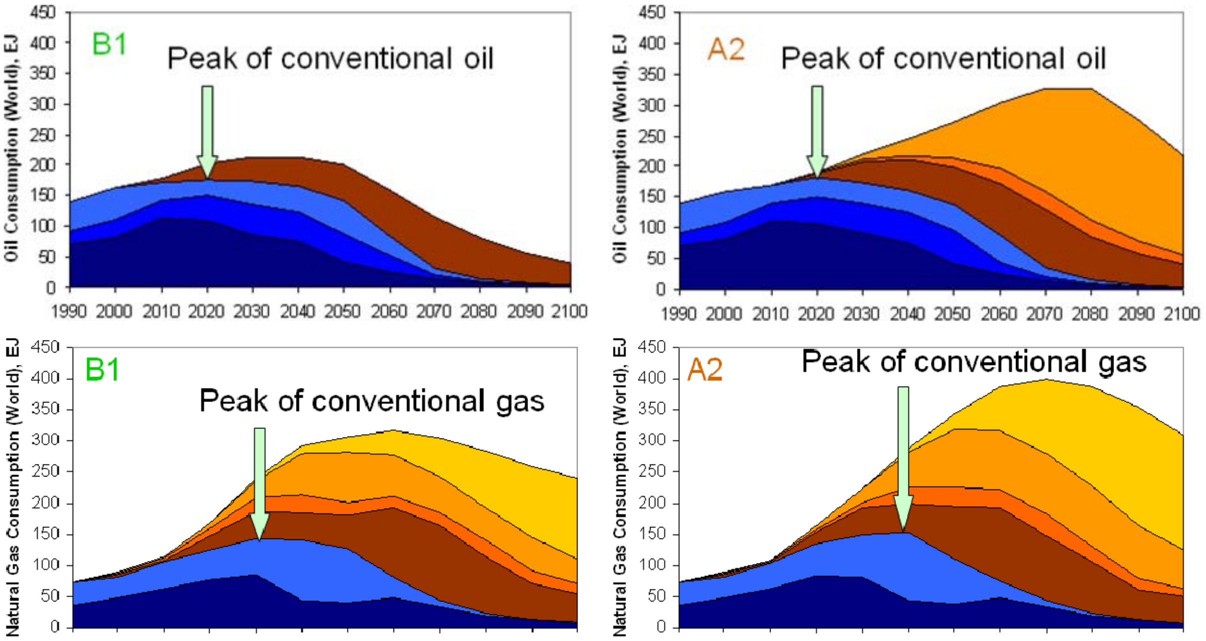
Table 13 Global oil and gas energy reserves, resources, and occurrences (in ZetaJoules).

	Consumption		**Reserves identified**	**Conventional resources remaining to be discovered**		**Recoverable with technological progress**	**Additional occurrences**
	1860-1990	1990		Low	High		
Oil	3.35	0.13	6.3	1.6	5.9		
Conventional	--	--	7.1			9	>15
Unconventional							
Gas							
Conventional	1.7	0.07	5.4	9.4	22.6		>10
Unconventional	-	-	6.9			20	>22
Hydrates	-	-					>800
Arctic gas (USGS) 2008							**1.794**

Sources: Nakicenovic et al., 1996; Nakicenovic, Grübler and McDonald, 1998; WEC, 1998; Masters et al., 1994; Rogner, 1997

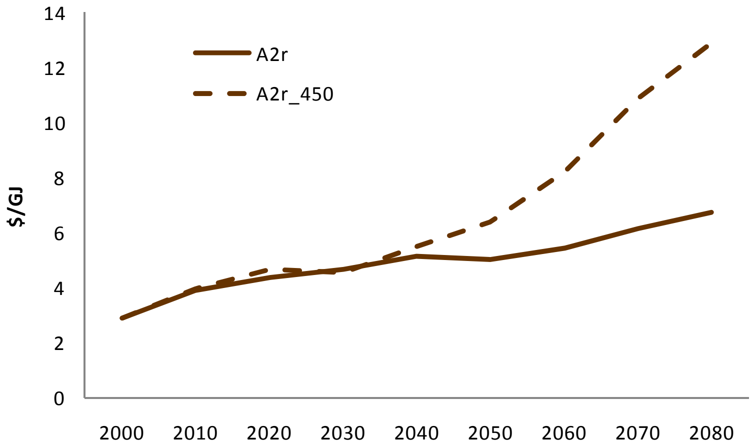
Assumptions on resource availability and technological change in the different scenarios determine how investments in the oil sector will evolve in the future. Fossil fuel use lies below resource availability in all scenarios, thus indicating that resource scarcity, albeit an important limiting factor for fossil fuel usage is not necessarily the only determinant for its use. As seen in Figure 33, the A2 scenario is characterized by high demand for and the rapidly growing pressure on fossil resources and the heavy dependence on oil for most of the century. With conventional oil becoming increasingly scarce, a shift toward more expensive unconventional oil sources takes place by 2050, with a doubling of investments and a further increase later in the century. The B1 scenario, which is based on a much lower energy demand and assumed higher rates of technological change, opts for alternatives to fossil fuels, causing the peak in coal and oil resources to occur much earlier. In general, the scenarios demonstrate that concerns about economic recoverability and the environment are more likely to initiate a future shift to other energy sources than are absolute resource constraints.

Figure 33 Oil and gas supply, B1 and A2 scenarios.



Natural gas and LNG in particular are expected to play a key role in the energy transition process over the next few decades, due to the advantages of natural gas as a relatively clean energy carrier. The competitiveness of gas as an energy source and the ability to find alternatives to gas are an important factor with reference to continued investments in this sector. In both scenarios, cumulative investments in the gas sector over the next 30 years lie in the range of USD 1–2 trillion[3]. This also highlights the significance of gas trade in the future, with gas-rich regions making large investments into production and transportation facilities. In addition, importing regions like Western Europe will also increase its investments in gas exploration and LNG facilities. This can be interpreted as the emergence of joint investments in gas facilities, with major importers making large-scale investments to facilitate the import of gas.

Figure 34 Natural gas fuel shadow prices in the A2r scenario.

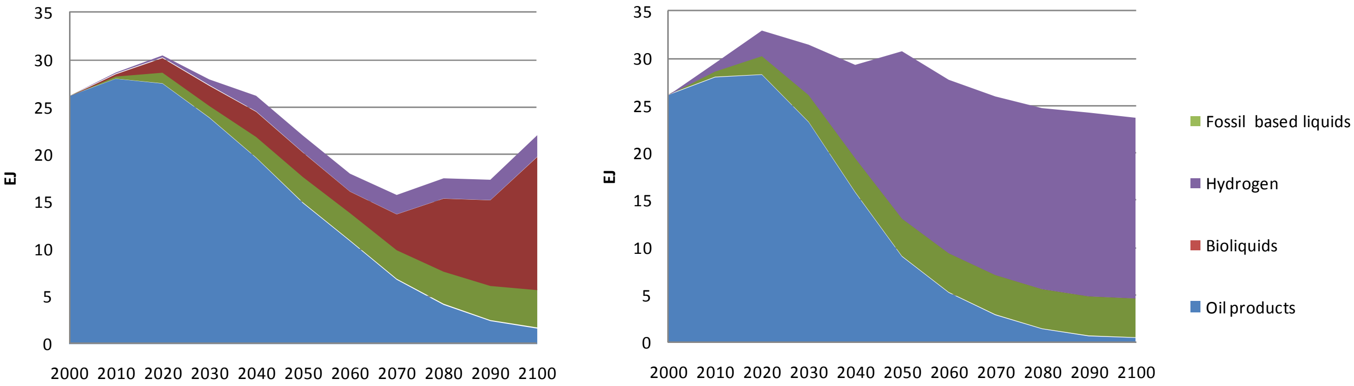


---

[3] The IEA (2004) estimates that approximately USD 3 trillion cumulative gas sector investments will have been made by 2030.

In the A2r scenario, fossil fuel prices increase (see, for example, natural gas prices in Fig. 34) due to the rise in energy demand and progressive depletion of low-cost fossil resources, especially in conjunction with ever-more stringent climate constraints. Technological innovation will be key in substantially lowering the costs of the current expensive alternatives. Alternative fuel use, including bio-liquids, fossil (coal and gas) based liquids, and hydrogen will be particularly important in regions that are dependent on oil and gas imports like Western Europe[4]. The increasing fuel prices will imply that such alternative fuels will be particularly important in filling the fossil fuel gap in the long term.

Figure 35 Synthetic fuel use in Western Europe (2000–2100).



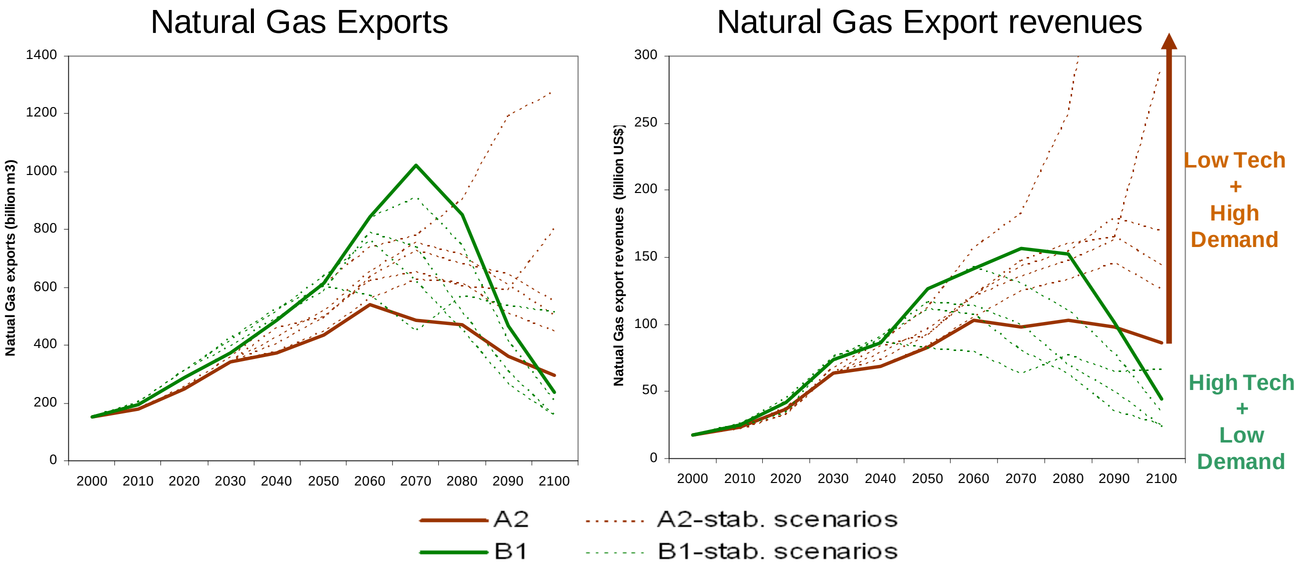
Investments in the oil and gas sector in the long term thus largely depend not only on fuel prices, but also on technological change in the energy system that supports the shift from oil-based fuels to alternatives. Synthetic fuels can substitute fossil-based fuels in many applications and can thus potentially play an important role in future energy supply. They assume special importance in regions that have rich coal, gas or biomass resources, since synthetic fuels only produce a fraction of the emissions generated by the consumption of normal gasoline or diesel fuels

Rising energy prices and the emergence of fossil alternatives can also be expected to significantly impact energy trade, which is also projected to undergo a transformation in the future. Figure 36 depicts future natural gas exports in both the A2r and B1 scenarios and the different cases of climate stabilization. The B1 scenario presents an overall decrease in gas imports in the future in all cases, while the A2r scenario continues to rely heavily on natural gas, even under more stringent climate stabilization constraints, thus indicating that it will be indispensible to increase energy efficiency and invest into technological innovations that can deliver alternatives, if the critical issue of fossil fuel imports is to be tackled. This has particular implications for climate mitigation policies of energy importing countries like Finland which should emphasize the role of such technological innovation in order to simultaneously reduce GHG emissions and dependence on energy imports.

---

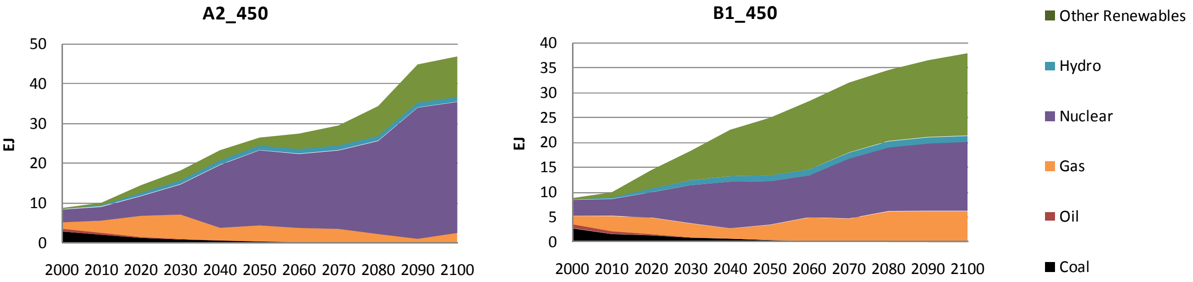
[4] According to IEA (2007), all fossil fuels required in Finland are imported, with net imports of electricity reaching 15–20% of total consumption, depending on the rainfall in the Nordic area. Of particular concern are imports from Russia, which supplies the entire country's gas, nearly all of its oil and 10% of its electricity.

Figure 36 Global natural gas exports from former Soviet Union, 2000–2100, Billion m^3.



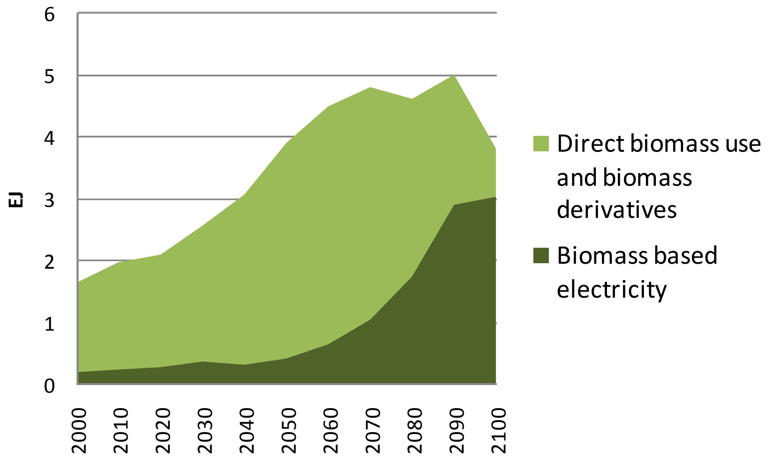
Electricity generation profiles are also expected to change in the future in order to respond to rising fossil fuel prices and the need to respond to climate change. Figure 37 illustrates the response to a 450 ppm CO_2-equivalent target under the A2r and B1 scenarios. It is anticipated that low carbon options like nuclear and renewable based electricity will play a major role in regions like Western Europe in the future to mitigate climate change, although the extent of these options may vary depending on the technological choice and costs. These results indicate that current national policies in countries like Finland, which support an increase in the contribution by nuclear power, as well as the adoption of more renewable energy (in particular biomass) can be compatible with low climate futures.

Figure 37 Electricity generation, Western Europe, A2_450 and B2_450.



Biomass can be an important source of energy through the direct use of biomass, as well as bioliquids which can be used to substitute oil products in certain areas such as transport. The scenarios include a detailed presentation of different price-based bioenergy potentials in the different regions, taking into account land constraints and food demands (for a more detailed discussion, see Riahi et al., 2006). We observe that an increase in fossil fuel prices implies that biomass becomes more competitive. An additional factor of biomass-based energy is that it is essentially carbon neutral (within short timeframes) and can thus play an important role in reducing GHG emissions. The importance of advanced technologies like biomass energy in combination with carbon capture and storage (BECS) is expected to increase in light of more stringent climate targets, due to their large potential in reducing the overall costs of mitigation. Results from our analysis also indicate that the implementation of climate policies may lead to fundamental changes in the economics of the agriculture and forestry sectors. This concerns, in particular, new markets and business opportunities through additional revenues from afforestation and bioenergy activities in these sectors (e.g., through GHG permits). This can be a significant economic boost for countries like Finland which already derive a large part of their economic revenue from these sectors.

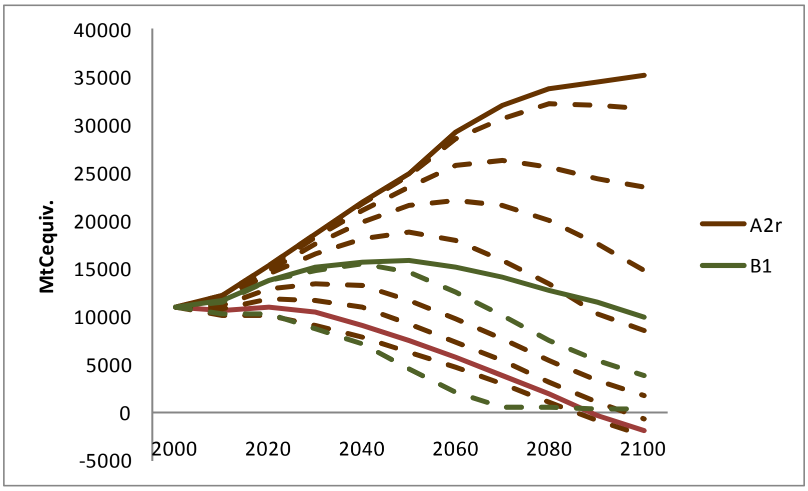
Figure 38 Biomass use in Western Europe in A2_450.



Thus from the perspective of energy supply options, those with the highest degrees of versatility in the production of a large variety of fuels suited for different end-use applications (gases, liquids, and electricity) generally emerge as the most robust technology options in both scenarios. These are natural gas in the short term (if available) and biomass in the long term (produced outside the traditional energy sector, i.e., in agriculture and forestry). Other renewables (solar, wind, and hydropower) and nuclear power are important mitigation options, but their potential contribution may be limited by energy-conservation efforts, as well as by their integration into the overall energy systems architecture.

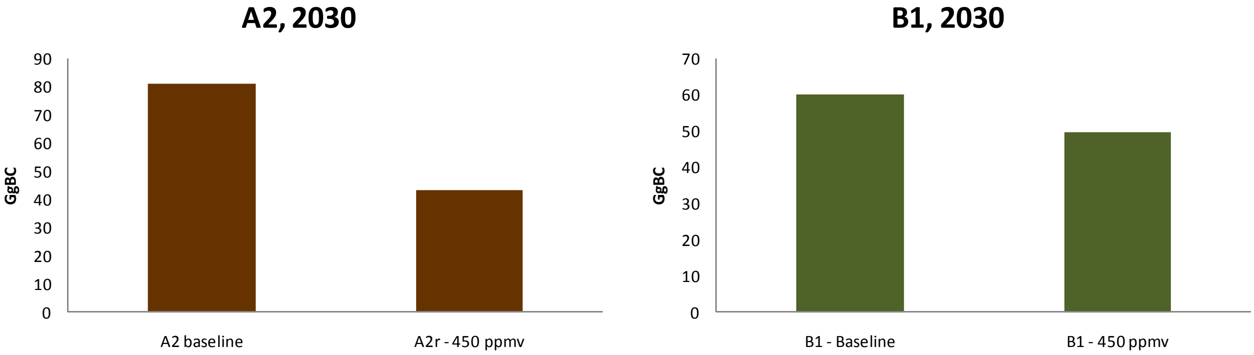
The diverging patterns of energy use are reflected in the GHG emission profiles shown in Figure 38, with total carbon equivalent emissions ranging from 9–37 GtCequiv by the end of the century in the absence of specific climate policies. Compared with today's emissions rate, the rate in the A2r scenario increases by more than 3 times, while that in the B1 scenario leads to slightly lower levels due to lower demands and higher technological change. The drivers for high and low emissions in the two scenarios are both scenario- and sector-specific. For instance, the high carbon emissions in the A2r scenario are dominated by the high emissions of the energy sector, which are a result of the high increase in demand owing to the combined effects of high population growth and more limited efficiency improvements. These are coupled with slower rates of technology improvement that result from lower productivity growth. Conversely, the high emissions for CH_4 and N2O in A2r result primarily from the rise in the demand for agricultural products, which reflects the dominance of this sector with reference to these two GHGs.

Figure 39 World GHG emissions, MtC equivalent.



To achieve climate stabilization, the rates of decarbonization would have to be accelerated to beyond those of the baseline scenarios. Perhaps even more importantly, in order to achieve extremely low stabilization levels, emissions would have to be reduced to below zero levels. This implies in the most stringent stabilization scenario that, in addition to low emissions, extensive carbon management is also required in the form of carbon sequestration and disposal, as reflected in the negative values for carbon intensities toward the end of the 21st century. This indicates that a completely new paradigm is required for the conceptualization and development of such very low GHG scenarios of the future.

Figure 40 Energy sector black carbon emissions, Western Europe, 2030.



An important point is that climate mitigation policies, especially for stringent GHG reductions, can bring significant co-benefits by reducing air pollutants, as many GHGs and air pollutants are often emitted from the same sources. While the reduction of such local pollutants has obvious benefits in terms of environmental quality and health, quantifying such benefits is quite a complex task. One of the main reasons is the different spatial and temporal scales of GHG emissions as compared to local pollutants. Another factor is that the climatic impacts of GHGs and pollutants can often be very different, for example, SO2 has a cooling effect on the climate, and sulfur emissions reduction may imply an increase in global warming. While quantifying such benefits is difficult, it is plausible that accounting for such benefits while calculating the costs of climate mitigation can significantly change a particular region’s perception of the losses it may suffer from participating in climate mitigation efforts. Thus, it is necessary to carefully examine the linkages between climate policy and local pollutants in order to develop an integrated or multi-objective policy framework that produces the overall desired effects (Rao et al., 2005).

7 BIBLIOGRAPHY

ACIA (2004) Impacts of Warming Arctic: Arctic Climate Impact Assessment. Cambridge, UK: Cambridge University Press.

ACIA (2005) Arctic Climate Impact Assessment. Cambridge University Press, New York, 1042 pp.

AC-SAO (2009) Meeting of Senior Arctic Officials, 12-13 November 2009, Copenhagen, Final Report, AC-SAO-NOV09; available from: http://www.arctic-council.org/

Alcamo, J., Dronin, N., Endejan, M. et al. (2003) A new prospect on the impacts of climate change on Russian agricultural and water resources // World Climate Conference, Abstracts. – Moscow, p. 73.

AMAP (2009) Update of Selected Climate Issues of Concern. AMAP, Oslo, ISBN 978-82-7971-049-3.

Anisimov, O. A. (2003) Climate change and permafrost: impacts on northern infrastructure // World Climate Conference, Abstracts, Moscow, p. 232.

Anisimov, O. A. & Beloluzkaya, M. A. (2003) Impact of climate change on permafrost: Forecast and estimation of uncertainty. Problems of Ecological Monitoring and Modelling of Ecosystems, ed. by A.Israel, Hydrometeoizdat, St.Petersburg, pp. 21-38.

Arctic Council (2009) Arctic Marine Shipping Assessment 2009 Report (AMSA), Arctic Council, April 2009, 2nd edition.

Bond, T. C., Streets, D. G. Yarber, K. F., Nelson, S. M., Woo, J.-H. and Klimont, Z. (2004) A technology-based global inventory of black and organic carbon emissions from combustion. Journal of Geophysical Research, Vol. 109, D14203, doi:10.1029/2003JD003697

Cofala, J., Amann, M., Klimont, Z., Kupiainen, K., Höglund-Isaksson, L. (2007) Scenarios of Global Anthropogenic Emissions of Air Pollutants and Methane Until 2030. Atmospheric Environment, 41:8486-8499, doi:10.1016/j.atmosenv.2007.07.010.

Corbett, J.J., D.A. Lack, J.J. Winebrake, S. Harder, J.A. Silberman, and M. Gold (2010) Arctic shipping emissions inventories and future scenarios. Atmos. Chem. Phys. Discuss., 10, 10271-10311

Dai, A., Trenberth, K.E. & Qian, T. (2004) A global dataset of Palmer Drought Severity Index for 1870-2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology,* 5, 1117-1130.

Erzev, G. N., Barenboim, G. M. & Taskaev, A. I. (2000) Experience of elimination of breakdown oil spill in Usinsky district of Komi Republic. Syktivkar.

Federal Service on Hydrometereology and Monitoring of Environment of the Russian Federation (2010), Report on Climate Peculiarities in Territory of the Russian Federation in 2009. Federal Service on Hydrometeorology and Monitoring of Environment of the Russian Federation, Moscow, p. 57 [in Russian].

Flanner, M. G., Zender, C. S., Hess, P. G., Mahowald, N. M., Painter, T. H., Ramanathan V., Rasch, P. J. (2009) Springtime warming and reduced snow cover from carbonaceous particles. Atmos. Chem. Phys. 9, 2481–2497.

Frolov I.E. (2006) Climate change in polar regions. In: Israel Yu.A. (ed) Possibilities of Climate Change Prevention: the Kyoto Protocol Problem. Russian Academy of Sciences, Nauka Publisher, pp.129-133 [in Russian].

Frolov, E .I., Gudkovich, Z. M., Karklin, V. P., Smoljanitsky, V. M. (2006) Climatic variation of ice cover area in the Eurasian Arctic and expected change of these in 21th century. In: Israel Yu.A. (ed) Possibilities of Climate Change Prevention: the Kyoto Protocol Problem. Russian Academy of Sciences, Nauka Publisher, pp.353-370 [in Russian].

Frolov, I. E., Gudkovich, Z. M., Karklin V. P., Kovalev, E. G., Smolyanitsky, V. M. (2007) Climatic change of ice condition in Arctic Seas of the Eurasian Shelf. Problems of Arctic and Antarctic, No 75, 149-160.

Frolov, I. E., Gudkovich, Z .M., Karklin, V. P., Kovalev, E. G., Smolyanitsky, V.M. Climate Change in Eurasian Arctic Shelf Seas. Praxis Publishing, 2009. 164 p.

Fronzek, S., Johansson, M., Christensen, T. R., Carter, T. R., Friborg, T. and Luoto, M. (eds.) (2009) Climate Change Impacts on Sub-Arctic Palsa Mires and Greenhouse Gas Feedbacks. Proceedings of the PALSALARM symposium, Abisko, Sweden, 28-30 October 2008. *Reports of the Finnish Environment Institute* 3/2009, p. 74, Finnish Environment Institute.

Gavriliev, P.P. (2003) Permafrost thawing and the transformation of landscapes in Yakutia under global warming // World Climate Change Conference, Abstracts, Moscow, p. 559.

Gavrilova, M. K. (2007) Climate change in permafrost regions of Russia during the 20th century, Influence of Climate and Ecological Changes on Permafrost Ecosystems. – Yakutsk, pp. 9-15.

Grubler, A. et al. (2007) Regional, National, and Spatially Explicit Scenarios of Demographic and Economic Change Based on SRES. Technological Forecasting & Social Change (Special Issue: Greenhouse Gases - Integrated Assessment), 74(7) 980-1029.

Gruza, G., Bardin, M., Rankova, E. et al. (2002) Climate Change-2002. An outlook of state and tendencies of climate in Russia. Available at www.climate.mecom.ru.

Gudkovich, Z. M. et al. (2002) Variability of ice cover of Russian Arctic Seas in 20th century and estimate its possible change in 21th century. In: *Proceedings of the Workshop Hydro-meteorological Provision of Economic Activities in the Arctic and Freezing Seas*, S. Ptersburg, pp. 36-45 [in Russian].

Hansen, J.E. & Sato, M. (2001) Trends of measured climate forcing agents, Proc. Nat. Acad. Sci., 98(26), 14778.

Hansen J. & Nazarenko L. (2004) Soot climate forcing via snow and ice albedos. PNAS 101(2), 423-428.

Hetemäki & Hänninen R. (2009) Outlook for forest industry production and wood consumption for 2015 and 2020. Metla Workingpapers, No.122 (http://www.metla.fi/julkaisut/workingpapers/2009/mwp.htm).

Hirdman, D., Sodemann, H., Eckhardt, S., Burkhart, J. F., Jefferson, A., Mefford, T., Quinn, P.K., Sharma, S., Strom, J. & Stohl, A. (2010) Source identification of short-lived air pollutants in the Arctic using statistical analysis of measurement data and particle dispersion model output. Atmos. Chem. Phys. 10, pp. 669–693.

IEA (2007) Energy Policies of IEA Countries, Energy Policies of IEA Countries: Finland 2007, International Energy Agency, OECD; Paris.

IEA (2008) World Energy Outlook, 2008, International Energy Agency, OECD, Paris.

IEA (2009) World Energy Outlook 2009. International Energy Agency (IEA). IEA-OECD, Paris.

IMO (2010) Prevention of Air Pollution from Ships. Reduction of emissions of black carbon from shipping in the Arctic. Submitted by Norway, Sweden and the United States. Marine Environment Protection Committee 60th session, Agenda item 4. 15 Jan 2010.

Intergovernmental Panel on Climate Change: Climate Change 2001: The Scientific Basis (2001), Summary for Policy Makers – Contribution of Working Group I to the Third Assessment Report of IPCC. Cambridge University Press, Cambridge, 2001

International Boundaries Research Unit (2008) Maritime jurisdiction and boundaries in the Arctic region (map). Durham University, UK.

IPCC (2007) Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, ("IPCC 2007"), available on the Internet at: http://ipcc-wg1.ucar.edu/wg1/wg1-report.html

Ivanov, B. I., & Maximov, T. C. (2003) Influence of Climatic and Ecological Changes on Permafrost Ecosystems. – Yakutsk, YD Publishing House SD RAS, pp. 332.

Jackson, S.C. (2009) Parallel pursuit of near-term and long-term climate mitigation, Science, 526.

Kajii Y., Kato S., Streets D., et al. (2003) Vegetation fire in Russia in 1998: Estimation of area and emissions of pollutants by AVHRR satellite data, Journal of Geophysical Research, 108, doi:10.1029/2001JD001078.

Khvorostyanov, D. V., Krinner, G., Ciais, P. et al. (2008a) Vulnerability of permafrost carbon to global warming. Part I: model description and role of heat generated by organic matter decomposition. Tellus 60B, 250-264.

Khvorostyanov, D.V., Ciais, P., Krinner, G. et al. (2008b) Vulnerability of permafrost carbon to global warming. Part II: sensitivity of permafrost carbon stock to global warming. Tellus 60B, 265-275.

Kiesewetter G. (2009) Assessing Transport of PM Pollution from Europe to the Arctic. IIASA interim report IR-09-038.

Kilpeläinen A., Kellomäki S., Strandaman H., Venäläinen A. (2010) Climate Change Impacts on Forest Fire Potential in Boreal Conditions in Finland. Climatic Change, DOI 10.1007/s10584-009-9788-7.

Klimont Z. (2009) White paper for black carbon. IIASA Options winter 2009/2010, 11.

Kondratiev K.Ya. (2004) uncertainties of observational data and numerical modeling of climate. *Meteorology and Hydrology*, No 2, pp. 93-119 [in Russian].

Korytnyi, L.M. (2009) Urgent tasks of geographical resources management. *Resource Economics, Environmental Economics and Climate Change-2009.* Krasnoyarsk, July 1-7 2009, Siberian Federal University, 359-366.

Krey V. et al. (2009) Gas Hydrates: Entrance to a Methane Age or Climate Threat? Environmental Research Letters, 4(3):034007 (7 September 2009).

Krukov, V.A. & Tokarev, A.N. (2009) Regulatory scheme and efficiency of oil and gas resource development. *Resource Economics, Environmental Economics and Climate Change-2009.* Krasnoyarsk, July 1-7 2009: Krasnoyarsk, Siberian Federal University, 367-383

Kupiainen, K. & Klimont, Z. (2007) Primary emissions of fine carbonaceous particles in Europe. Atmospheric Environment 41(10): 2156-2170, doi:10.1016/j.atmosenv.2006.10.066.

Kupiainen K. & Karvosenoja N. (2010) Emissions of BC and OC as estimated with the Finnish Regional Emission Scenario Model of the Finnish Environment Institute (SYKE). Memorandum for the meeting of the Arctic Council Task Force on Short-Lived Climate Forcers. 4 Feb 2010.

Lapenis, A., Shvidenko, A., Shepaschenko, D., Nilsson, S. & Aiyyer, A. (2005) Acclimation of Russian forests to recent changes in climate. *Global Change Biology,* 11**,** 2090-2102.

Law, K. S. & Stohl, A. (2007) Arctic air pollution: Origins and impacts. Science 315, 1537-1540, doi: 10.1126/science.1137695

Masters, C. D., Attanasi, E. D. and Root, D. H. (1994) World petroleum assessment and analysis. In:Proceedings of the 14th World Petroleum Congress, Stavanger, Norway. John Wiley, Chichester, UK.

Matala J., Käkkäinen L., Härkönen K., Kellomäki S., Nuutinen T. (2009) Carbon sequestration in the growing stock of trees of Finland under different cutting and climate scenarios. *European Journal of Forest Research* 128, 493-504.

Mattila V., Granholm H., Laanikari J., Yrjola T. Aalto A., Heikinheimo P., Honkatukia J., Jarvinen H., Liski J., Merivirta R & Paunio M. (eds) (2005) Finland's National Strategy for Adaptation to Climate Change. Publications of the Ministry of Agriculture and Forestry 1a/2005. Ministry of Agriculture and Forestry. Vammalan kirjapaino Oy, Vammala, Finland, 280 p

Mcguire, A.D., Sitch, S., Clein, J.S., Dargaville, R., Esser, G., Foley, J., Heimann, M., Joos, F., Kaplan, J., Kicklighter, D.W., Meier, R.A., Melillo, J.M., Moore Iii, B., Prentice, I.C., Ramankutty, N., Reichenau, T., Schloss, A., Tian, H., Williams, L.J. & Wittenberg, U. (2001) Carbon balance of the terrestrial biosphere in the twentieth century: Analyses of CO_2, climate and land use effects with four process-based ecosytem models. *Global Biogeochemical Cycles,* 15**,** 183-206.

Mekush, G.E. & Mekush, V.A. (2009) Economic growth and stability of regional development (by thr example of Kemerovo region). *Resource Economics, Environmental Economics and Climate Change-2009.* Krasnoyarsk, July 1-7 2009: Siberian Federal University, 384-392

Meleshko, V.P., Katsov, V.M., Govorkova, V.A. et al. (2008) Climate of Russia in the XXI century. 3. Future climate changes obtained from an ensemble of the coupled atmosphere-ocean GCM CMIP3 // Meteorolgy and Hydrology, No 9., pp. 5-22.

Melnikov V.P., Pavlov A.V. (2006) Climate change in Russian North and geocryologic consequences. In: Israel Yu.A. (ed) Possibilities of Climate Change Prevention: the Kyoto Protocol Problem. Russian Academy of Sciences, Nauka Publisher, pp. 341-352 [in Russian].

Molina, M., Zaelke, D., Sarma, K. M., Andersen, S. O., Ramanathan, V., and Kaniaru, D. (2009) Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO_2 emissions, PNAS, 106(49), 20616-20621.

Musin M. (2007) Russian forests or how theft of billions dollars is organized // Russian Federation Today, No 5, pp. 56-57 [in Russian].

Myneni, R. B., Keeling, C. D., Tucker, C. J., Asrar, G. & Nemani, R. R. (1997) Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature,* 386**,** 698-702.

Nagaeva, O. S. (2009) The evaluation of the possibilities for a sustainable socio-economic development of the Northern regions of Krasnoyarsk krai under the conditions of oil and gas resources development. *Resource Economics, Environmental Economics and Climate Change-2009.* Krasnoyarsk, July 1-7 2009: Siberian Federal University, pp.72-85

Nakicenovic, N., et al. (1996) Energy primer. In R.T. Watson, M.C. Zinyowera and R.H. Moss (eds): Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change, The Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, pp. 77-92

Nakicenovic, N., Grübler, A. and McDonald, A. (eds.) (1998) Global Energy Perspectives. Cambridge University Press, Cambridge, UK.

Nakićenović et al. (2000) Special Report on Emissions Scenarios (SRES) for the Intergovernmental Panel on Climate Change., Working Group III, Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK..

On backgrounds of state policy of the Russian Federation in regions of the North, 2004. Available at http://www.kremlin.ru/text/appears2/2004/04/28/97302.shtml (in Russian)

Onuchin, A.A., Burenina, T.A. The hydrological role of forest in Siberia // Trends in Water Resources. - Nova Science Publishers, 2008. - P. 144-170.

Palmer, W.C. (1965) Meteorological Drought. Dept. of Commerce, Washington, D.C., Res. Paper 45**,** 58.

Peltonen-Sainio P., Rajala A., Känkänen H., Hakala K. (2009a) Improving farming systems in northern European conditions. In: V.O.Sadras and D.F. Calderini (eds.) Crop Physiology. Applications for Genetic Improvements and Agronomy. Elsevier, Amsterdam, pp. 71-97.

Peltonen-Sainio P., Jauhianen L., Laurila I.P. (2009b) Cereal yield trends in northern European conditions: Changes in yield potential and its realization. Field Crops Research 110, 85-90.

Peltonen-Sainio P., Jauhianen L., Hakala K., Ojanen H. (2009c) Climate change and prolongation of growing season: Changes in regional potential for field crop production in Finland. Agricultural and Food Science, 19, 171-190.

Pettus, A., (2009) Agricultural Fires and Arctic Climate Change: A Report for the Clean Air Task Force (CATF). www.catf.us, Boston, US.

Pryazhinskaya, V.G. (2009) Water use management methods under climate change. *Resource Economics, Environmental Economics and Climate Change-2009.* Krasnoyarsk, July 1-7 2009: Krasnoyarsk, Siberian Federal University, 133-147.

Quinn, P. K., Bates, T. S., Baum, E., Doubleday, N., Fiore, A. M., Flanner, M., Fridlind, A., Garrett, T. J., Koch, D., Menon, S., Shindell, D., Stohl, A., and Warren, S. G. (2008) Short-lived pollutants in the Arctic: their climate impact and possible mitigation strategies, Atmos. Chem. Phys. 8, 1723–1735.

Rao S, Riahi K, Kupiainen K, Klimont, Z (2005). Long-term scenarios for black and organic carbon emissions. *Environmental Sciences*, 2(2-3):205-216

Rao, S. and K. Riahi (2006). "The Role of Non-CO_2 Greenhouse Gases in Climate Change Mitigation: Long-term Scenarios for the 21st Century." The Energy Journal Special Issue #3: 177-200.

Riahi, K., A. Gruebler and N. Nakicenovic (2007). "Scenarios of long-term socio-economic and environmental development under climate stabilization." (Special Issue: Greenhouse Gases - Integrated Assessment) 74(7): 887–935.

Robledo, C., Blaser, J., Byrne, S., et al. (2008) Climate Change and Governance in the Forest Sector. Rights and Resources Institute, Washington, D.C., p. 61.

Rogner, H. H. (1997) An assessment of World hydrocarbon resources. Annual Review of Energy and the Environment 22, pp.:217-262.

Romanovsky, V. E., Shender, N. I., Sazonova, T. S., Balobaev, V. T., Tipenko, G. S. & Rusakov, V. G. (2001) Permafrost temperatures in Alaska and East Siberia: past, present and future. *Proceedings of the Second Russian Conference on Geocryology (Permafrost Science).* Moscow, June 6-8, 301-314.

Romashova, T. V., 2004. *Seasonal climatic rhythms and their impact on soil erosion* Tomsk, Positiv Publ. [in Russian]

Royal Society (2009) Geoengineering the climate. Science, governance and uncertainty. RS Policy document 10/09. Issued: September 2009 RS1636. (http://royalsociety.org/Geoengineering-the-climate/)

Ruosteenoja, K., Carter, T. R., Jylhaм, K. & Tuomenvirta, H. (2003) Future climate in world regions: An intercomparison of model-based projections for the new IPCC emissions scenarios. The Finnish Environment*,* 644**,** 644.

Sarofim, M. C., DeAngelo, B. J., Grano, D., Meitiv, D. L., Alnes, L.W.H., Rive, N., Berntsen, T., Mideksa, T. K., Myhre, G., Skeie, R. B., Klimont, Z., Weitz, K. A., Zapata, A., Bahner, M. A., Zaitchik, B. (2009) Current Policies, Emission Trends and Mitigation Options for Black Carbon in the Arctic Region. Draft White Paper by an Ad Hoc Working Group. AMAP (www.iiasa.ac.at/rains/reports/DRAFTWhitePaper-BCArcticMitigation-280909.pdf)

Sheingauz, A.S. Forest Complex of Khabarovsk Kray. - Kabarovsk, RIOTIP (2001), p. 210 [in Russian].

Schiermeier (2010) Space probe set to size up polar ice. Nature 464, p. 658.

Shiklomanov, I., Georgievsky, A., Yu, V. (2007) Change of river runoof under global warming, Proceedings of the VI Hydrological Congress, Moscow, pp. 159-163 [in Russian]

Shindell D. & Faluvegi G. (2009) Climate response to regional radiative forcing during the twentieth century. Nature Geoscience 2, 294-300, doi:10.1038/NGEO473.

Sirotenko, O. D., Abashina, E. V (2008) Current climatic changes of productivity of the biosphere of Russia and contiguous countries / Meteorology and Hydrology, 2008, No 4, pp. 101-107.

Somanathan S., Flynn P. C. and Szymanski, J. (2006) The Northwest Passage: A Simulation. Proceedings of the 2006 Winter Simulation Conference, 1578-1585.

Stohl, A. (2006) Characteristics of atmospheric transport into the arctic troposphere, J. Geophys. Res., 111, D11306, doi:10.1029/2005JD006888.

Streets, D.G., Bond, T.C., Lee, T. and Jang, C. (2004) On the future of carbonaceous aerosol emissions. Journal of Geophysical Research-Atmospheres, 109(D24)

Tchebakova, N. M., Parfenova E. I., Rehfeldt, G. E. (2003) Climate warming impacts on forests of Central Siberia // World Climate Change Conference, Moscow, pp. 528-529.

Tollefson, J. (2010) Geoengineers get the fear. Nature, 464, p.656

UN Program of Development in Russia (2009), Russian Regional Ecological Center, Complex climatic strategies for sustainable development of regions of the Russian Arctic under climate change, Moscow, UN Program of Development in Russia, Russian Regional Ecological Center [in Russian].

UNECE (2009) UNECE CLRTAP, Report of the Executive Body on its twenty-seventh session, 14-18 December 2009, Geneva, ECE.EB.Air/99/

UNEP (2009a) Black Carbon e-Bulletin. United Nations Environment Programme (UNEP). Vol.1, Number 2, September; UNEP, 2009b. Black Carbon e-Bulletin. UNEP. Vol.1, No. 3

USGS (2008) Circum-Arctic Resource Appraisal: Estimates of Undiscovered Oil and Gas North of the Arctic Circle

Venäläinen A., Tuomenvirta H., Heikinheimo M., Kellomäki S.,Peltola H., Strandman H. and Väisänen H. (2001a) The impact of climate change on soil frost under snow cover in a forested landscape. Climate Research 17, 3-72

Venäläinen A., Tuomenvirta H., Lahtinen R. ja Heikinheimo M. (2001b) The influence of climate warming on soil frost on snow-free surfaces in Finland. Climatic Change 50(1/2), 111-128.

Verny J. & Grigentin C. (2009) Container Shipping on the Northern Sea Route. Int. J. Production Economics 122, 107-117.

Wagner, D., Gattinger, A., Embacher, A., Pfeiffer, E.M., Schloter, M. & Lipski, A. (2007) Methanogenic activity and biomass in Holocene permafrost deposits of the Lena Delta, Siberian Arctic and its implication for the global methane budget. *Global Change Biology,* 13**,** 1089-1099.

Yefremov, D. F., Shvidenko, A. Z. (2004) Long-period ecological consequences of catastrophic fires in Far Eastern forests and their contribution into global processes // Forest Fire Management at Ecoregional Level, Moscow, Alex Publ., pp. 66-73.

Zabelina, I. A. (2009) Quantitative assessment of economic development inequality and distribution of ecological load between the Russian Federation Regions. *Resource Economics, Environmental Economics and Climate Change-2009.* Krasnoyarsk, July 1-7 2009: Siberian Federal University, 45-56

Zimov, S. A, Schuur, E. A. G., Chapin, F. S. (2006) Permafrost and the global carbon budget. Science 312, 1612-1613

PRIME MINISTER'S OFFICE
FINLAND

SNELLMANINKATU 1, HELSINKI
PO BOX 23, FI-00023 GOVERNMENT, FINLAND
Tel. +358 9 16001, +358 9 57811
Fax +358 9 1602 2165
julkaisut@vnk.fi
www.vnk.fi/english