Arctic Climate Impact Assessment (ACIA)

AMAP Report 2004:4

The ACIA International Scientific Symposium

on

Climate Change in the Arctic

Extended Abstracts

Reykjavik, Iceland, 9 - 12 November 2004

Preface

This volume comprises the extended abstracts of oral and poster presentations at the *ACIA International Scientific Symposium on Climate Change in the Arctic*, Reykjavik, 9-12 November 2004, organized by the Arctic Climate Impact Assessment (ACIA). The Arctic Climate Impact Assessment is conducted under the auspices of the Arctic Council working groups: Arctic Monitoring and Assessment Programme (AMAP) and Conservation of Arctic Flora and Fauna (CAFF), in association with the International Arctic Science Committee (IASC).

Abstracts are arranged according to the symposium sessions, oral sessions first, followed by poster sessions. A list of contents follows this introduction.

The Symposium is an important part of the process by which the results and conclusions of the Arctic Climate Impact Assessment will be communicated to Arctic stakeholders and to Ministers at the Fourth Arctic Council Ministerial Meeting in Reykjavik, November 2004.

ACIA gratefully acknowledges the countries and organizations that have sponsored the Symposium and/or participated in its arrangement, and welcomes all participants to Reykjavik.

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Contents

Session 1: Wednesday 10 November

Oral Presentations: Past, Present and Future Changes in Physical Systems

1.1	The Changing Arctic Climate: Historical Observations and Recent Explanations *James E. Overland*	James E. Overland
1.2	Spatial and Temporal Mapping of Temperature Variability in Iceland since the 1870's *Halldór Björnsson and Trausti Jónsson*	Halldór Björnsson
1.3	Joint Roles of the Panarctic Shelf Break and Retreating Summer Ice in Arctic Warming *Eddy Carmack, William Williams, Fiona McLaughlin and David Chapman*	Harald Loeng
1.4	The Ob River: Is there Arctic Inflow Increase? *L. Agafonov*	L. Agafonov
1.5	Linkage between Sea-ice Distribution and Snow-precipitation may considerably affect Terrestrial Ecosystems in Future High Arctic Climates *Jørgen Hinkler, Birger U. Hansen, Mikkel P. Tamstorf and Hans Meltofte*	Jørgen Hinkler
1.6	Climate Records from Temperate Ice Caps in Iceland: Pilot Studies on Hofsjökull *Th. Thorsteinsson, O. Sigurdsson, T. Jóhannesson, G. Larsen and H. Oerter*	Th. Thorsteinsson
1.7	Thermokarst Development in a Changing Climate *Larry D. Hinzman, Horacio A. Toniolo, Kenji Yoshikawa, Jeremy B. Jones*	Larry D. Hinzman
1.8	A Climatic Perspective on Observed Arctic Permafrost Changes *Ole Humlum*	Ole Humlum
1.9	Response of Glaciers in Iceland to Climate Change *Tómas Jóhannesson, Guðfinna Aðalgeirsdóttir,* *Helgi Björnsson, Finnur Pálsson and Oddur Sigurðsson*	Tómas Jóhannesson
1.10	Establishment of Decadal-scale UV Climatologies for High-latitude Ecosystems Studies *Georg Hansen, Ola Engelsen, Kåre Edvardsen, Jean Verdebout, Ralf Meerkötter, Luca Bugliaro and Angel Borja*	Georg Hansen

Session 2: Wednesday 10 November

Oral Presentations: Past, Present and Future Changes in Biological Systems

2.1	Marine Ecosystem Responses to the Warming of 1920s and 1930s *Kenneth F. Drinkwater*	Kenneth F. Drinkwater
2.2	Biological Implications of Arctic Change *Jackie M. Grebmeier and Lee W. Cooper*	Jackie M. Grebmeier
2.3	Ecosystem Changes in High Arctic Marine Ecosystems *Søren Rysgaard*	Søren Rysgaard
2.4	Anadromous Arctic Fishes and Impacts of Climate Change *Jacquelynne R. King and Richard J. Beamish*	Jacquelynne R. King
2.5	Char as a Model for Assessing Climate Change Impacts on Arctic Fishery Resources *James D. Reist, Michael Power and J. Brian Dempson*	James D. Reist
2.6	Trend Coincidence of Pink Salmon Catch Dynamics among the Odd-years and Even-years Populations as an Evidence of Large-scale Physical Factors Effect *Vladimir I. Radchenko*	Vladimir I. Radchenko
2.7	Palaeolimnological Evidence for Recent Climate Change in Lakes from the Northern Urals, Arctic Russia *Nadia Solovieva, Vivienne J. Jones, Larisa Nazarova, Stephen J. Brooks, H. J. B. Birks, John-Arvid Grytnes, Peter G. Appleby, Tommi Kauppila, Boris Kondratenok, Ingemar Renberg, and Vasily Ponomarev*	Nadia Solovieva
2.8	Climate, Snow and Hydrology in Tundra Ecosystems: Patterns, Processes, Feedbacks and Scaling Issues *Bob Baxter, Brian Huntley, Richard J Harding, Terry V. Callaghan, Philip A Wookey, Andrew M Fox, Colin R Lloyd, David R Sayer, James G Cook and Andrew J Wiltshire*	Bob Baxter

2.9	Responses of Tundra Ecosystems to Environmental Change: Observational and Experimental Results from the International Tundra Experiment (ITEX) *Greg H.R. Henry*	Greg H.R. Henry
2.10	Climatogenic Dynamics of Biota within the Current Distributions of Organisms and their Communities in the Arctic and their Implications for Response to Climate Change *Nadezhda V. Matveyeva*	Nadezhda V. Matveyeva

Session 3: Wednesday 10 November

Oral Presentations: Possible Feedbacks on the Global Climate System

3.1	Integrated Carbon Balance Studies for European Arctic Catchments *Peter Kuhry, Lauri Arvola, Kapitolina Bobkova, Juha Heikkinen, Eeva Huitu, Pertti Martikainen, Galina Mazhitova, Kari Mikkola and Tarmo Virtanen*	Peter Kuhry
3.2	Effects on the Carbon Balance of High-Arctic Tundra: Entire Growing Season Warming Versus Heat Wave Exposure *Fleur Marchand, Ivan Nijs and Louis Beyens*	Fleur Marchand
3.3	Land Surface Radiation Budget Response to Global Warming: Case Study for European and Asian Radiometric Network *O.M. Pokrovsky, E.L. Makhotkina, I.O. Pokrovsky, L.M. Ryabova*	O.M. Pokrovsky
3.4	Possible Feedbacks on Arctic Cloud Formation: Can the Arctic Biosphere Affect the Melting of the Ice? *Caroline Leck and Michael Tjernström*	Caroline Leck
3.5	How Good is the Surface Energy Balance in Current Atmospheric Climate Models? *Michael Tjernström, Mark Žagar and Gunilla Svensson*	Michael Tjernström

Session 4: Wednesday 10 November

Oral Presentations: Impacts on Wildlife and Conservation / Policy issues

4.1	Climate Change, Sea Ice Conditions, and Effects on Marine Birds in Arctic Canada *H. Grant Gilchrist, Anthony J. Gaston and Mark J. Mallory*	H. Grant Gilchrist
4.2	Climate Change and Goose Grazing on Svalbard's Tundra *Elisabeth Cooper, Ingibjörg Svala Jónsdóttir, Dominique Chaput, Dries Kuijper, Maarten Loonen, Astrid Pahud, Sofie Sjögersten, Richard Ubels, René van der Wal, Sarah Woodin and Ad Huiskes*	Elisabeth Cooper
4.3	Vulnerability of Arctic Shorebirds to Climate Variability and Change *Hans Meltofte, Theunis Piersma, Hugh Boyd, Brian McCaffery, Viktor V. Golovnyuk, Katherine Graham, R.I.G. Morrison, Erica Nol, Doug Schamal, Hans Schekkerman, Mikhail Y. Soloviev, Pavel S. Tomkovich, Diane Tracy, Ingrid Tulp and Liv Wennerberg*	Hans Meltofte
4.4	Modeling the Response of Parasites in Arctic and Sub-arctic Ungulates to Climate Change *Susan Kutz, Eric Hoberg and Lydden Polley*	Susan Kutz
4.5	Mercury in the Arctic Ecosystem: Understanding Pathways of Contamination through Atmosphere and Biosphere *Noelle Eckley Selin, Daniel J. Jacob and Rokjin J. Park*	Noelle Eckley Selin
4.6	Biodiversity of Arctic Sea Ice Biota and Possible Effects of Oil Spills during Oil Transportation *Johanna Ikävalko and Birte Gerdes*	Johanna Ikävalko

Session 5: Thursday 11 November

Oral Presentations: Past, Present and Future Changes in Physical Systems (cont.)

5.1	Why Do Global Climate Models Project So Different Climates for the Arctic? *Gunilla Svensson and Thorsten Mauritsen*	Gunilla Svensson
5.2	The Sensitivity of Arctic Climate Projections to Natural Variability *Asgeir Sorteberg, Helge Drange, Tore Furevik and Nils Gunnar Kvamstø*	Asgeir Sorteberg

5.3	Long-term Climate Stability in the Québec-Labrador (Canada) Region: Evidence from Paleolimnological Studies *Reinhard Pienitz, Émilie Saulnier-Talbot, Marie-Andrée Fallu, Tamsin Laing, Karin Ponader, Kerrie Swadling and Ian Walker*	Reinhard Pienitz
5.4	Climate Change and Hydrology of the Large Siberian Rivers *Vitaly Kimstach, Lars-Otto Reiersen and Vladimir Grouzinov*	Vitaly Kimstach
5.5	Variations in Arctic Sea-Ice *Ignatius G. Rigor and John M. Wallace*	Ignatius G. Rigor
5.6	Polynya Variability in Arctic Shelf Areas as Inferred from Passive Microwave Imagery and Numerical Modeling *S. Kern and I. Harms*	S. Kern
5.7	On the Recent Time History and Forcing of the Inflow of Atlantic Water to the Arctic Mediterranean *Jan Even Ø. Nilsen, Hjálmar Hátún, Anne Britt Sandø, Ingo Bethke, Olivier Laurantin, Yongqi Gao, Helge Drange and Tore Furevik*	Jan Even Ø. Nilsen
5.8	Sensitivity to Climate Change in the Canadian High Arctic: Ellesmere Island Lakes, Fiords and Ice Shelf Ecosystems *Warwick F. Vincent, Patrick Van Hove, Derek R. Mueller and Martin O. Jeffries*	Warwick F. Vincent
5.9	Multivariate Statistical Analysis of Icelandic River Flow Series and Variability in Atmospheric Circulation *Jóna Finndís Jónsdóttir, Cintia B. Uvo and Árni Snorrason*	Jóna Finndís Jónsdóttir
5.10	Empirically Based Modelling of Variability and Trends in Local Snow Conditions *Inger Hanssen-Bauer*	Inger Hanssen-Bauer

Session 6: Thursday 11 November

Oral Presentations: Impacts on Human Activities

6.1	Variations in Climatic Constraints on Living Conditions in the Nordic Arctic, 1900-2050 *Eirik J. Førland and Inger Hanssen-Bauer*	Eirik J. Førland
6.2	Climate, Water and Renewable Energy in the Nordic Countries *Árni Snorrason and Jóna Finndís Jónsdóttir*	Árni Snorrason
6.3	Changing Marine Access in the Arctic Ocean - A Strategic View for the 21st Century *Lawson W. Brigham*	Lawson W. Brigham
6.4	Have Recent Biological Changes in Newfoundland Capelin (*Mallotus villosus*) occurred because of Physical Changes in the Arctic? *J. E. Carscadden, B. S. Nakashima and F. K. Mowbray*	J. E. Carscadden
6.5	Climate Change and Arctic Fisheries: Assessing the Economic and Social Impact in Iceland *Ragnar Arnason, Sveinn Agnarsson*	Ragnar Arnason
6.6	Scenarios of Social Response to Climate Change Impacts on Two Subsistence Resources in Interior Alaska: An Analysis of Resilience and Vulnerability *Chanda Meek, Alison Meadow, Anna Godduhn and Sherri Wall*	Chanda Meek
6.7	Vulnerability Assessment: The Role of Indigenous and Local Communities and Place-Based Assessments in Contributing to a Sustainable Arctic Future *David N. Roddick*	David N. Roddick
6.8	Indigenous Perspectives on Environmental Change in the Canadian Arctic: Community-based Vulnerability Assessment *Barry Smit, Johanna Wandel and James Ford*	Barry Smit
6.9	Physical, Biological and Human Coupling in a Traditional Ecological Knowledge-based Climate Change Model - Theory, Formalism and Interpretation *Raphaela Stimmelmayr*	Raphaela Stimmelmayr
6.10	Never-ending Perfect Circle of Seasons – SnowChange, Indigenous Knowledge and Education for a Post-Colonial Arctic *Elina Helander and Tero M. Mustonen (SnowChange Project, Finland)*	Tero M. Mustonen
6.11	On the Effect of Sea Ice on Icelanders' Lives from 1850 to the Present Day: Combining Historical Analysis and Remote Sensing through Geographical Information Systems *Ingibjörg Jónsdóttir*	Ingibjörg Jónsdóttir

Session 7: Thursday 11 November

Oral Presentations: Arctic-Global Connections and Assessing Impacts of Change

7.1	ArcticNet: A Newly Funded Network of Centres of Excellence of Canada to Conduct the Integrated Natural/ Human health/Social study of the Changing Coastal Canadian Arctic *Louis Fortier and Martin Fortier*	Martin Fortier
7.2	The National Oceanic and Atmospheric Administration (NOAA) Arctic Climate Change Studies: A U.S. Contribution to Arctic Council Response to the ACIA *John Calder, Taneil Uttal, James Overland, Jackie Richter-Menge, Ignatius Rigor and Kathleen Crane*	John Calder
7.3	Assessing Climate Change Vulnerabilities in the Barents Region through Integrated Regional Impact Studies *Manfred A. Lange (and the BALANCE Consortium)*	Manfred A. Lange
7.4	Kola Peninsula Climate Change in the Kola Saami Traditional Ecological Knowledge and Hydrometeorological Data *Sergey Zavalko, Alina Pisareva and Kyrill Zavalko*	Sergey Zavalko
7.5	Observational Evidence on Changes in the Thermohaline Coupling between the Arctic Mediterranean and the World Ocean *Bogi Hansen, Svein Østerhus and William R. Turrell*	Bogi Hansen
7.6	Assessing Vulnerabilities: A New Strategy for the Arctic *Bull, K.S., Corell, R.W., Eira, I.G., Eira, N.I., Eriksen, S., Hanssen-Bauer, I., Hovelsrud-Broda, G.K., Mathiesen, S.D., McCarthy, J.J., Long Martello, M., Nellemann, C., Oskal, N., Polsky, C., Reinert, E., Storeheier, P.V., Tyler, N.J.C. and Turi, J.M.*	K.S Bull
7.7	Long-term Observations of Cloudiness, Radiation and Aerosols with Permanent Atmospheric Observatories *Taneil Uttal, Shelby Frisch, Xuanji Wang and Jeffrey Key*	Taneil Uttal

Session 8: Thursday 11 November

Oral Presentations: Past, Present and Future Changes in Social Systems

8.1	Putting the Human Face on Climate Change through Community Workshops: Inuit Knowledge, Partnerships, and Research *Chris Furgal, Scot Nickels, Mark Buell (and communities of the regions of Labrador, Nunavik, Nunavut and the Inuvialuit Settlement Region)*	Chris Furgal
8.2	"It's Not That Simple": Bringing Together Inuit, Iñupiat and Scientists to Understand the Complexities of Changing Sea Ice and Its Uses in the North American Arctic *Shari Fox Gearheard, Geela Tigullaraq and Ilkoo Angutikjuak*	Shari Fox Gearheard
8.3	Climate Change Impacts and Athabaskan Peoples: the Denendeh Environmental Working Group, an Update on Activities. *C.D. James Paci*	C.D. James Paci
8.4	Vulnerability and Adaptive Capacity in Forestry, Fishing and Reindeer-Herding Systems in Northern Europe *E. Carina H. Keskitalo*	E. Carina H. Keskitalo
8.5	Harnessing Technologies for Sustainable Reindeer Husbandry in the Arctic *Nancy G. Maynard, Boris Yurchak, Johan Mathis Turi and Svein Mathiesen*	Nancy G. Maynard
8.6	Local and Traditional Knowledge in Assessing Climate Changes impacts on Sustainable Development: Russian and Circumpolar Perspectives *Tatiana K. Vlassova*	Tatiana K. Vlassova
8.7	Impacts of Climate Change on the Health of Northern Indigenous People *Keith Maguire and C. Dickson*	K. Maguire

Plenary Session 9: Friday 12 November

Oral Presentations: Looking to the Future (Keynote Speakers)

9.1	Coordinated Studies of the Russian Arctic During the International Polar Year 2007/2008 *A.V. Klepikov, A. I. Danilov, V. G. Dmitriev and M. Yu. Moskalevsky*	A.V. Klepikov

Poster Session A: Wednesday 10 November

Poster Presentations: Past, Present and Future Changes in Physical Systems

A1.1	The Interannual Variability of Arctic Ocean Temperature and Salinity Fields for Fifties-Eighties Derived by Assimilation of the Irregular Spaced Data *Oleg M. Pokrovsky and Leonid A. Timokhov*	Oleg M. Pokrovsky
A1.2	An Updated Estimation of Ground Ice Volume for Richard's Island in the Mackenzie Delta and an Assessment of Potential Thaw Sensitivity to Climate Change *Gregory P. De Pascale, Hugues Lantuit and Wayne H. Pollard*	Hugues Lantuit
A1.3	Why Is the Arctic Warming? Do Changes in the Mid-latitude Circulation Have Any Impact on the Arctic Surface Air Temperature Trend? *Rune G. Graversen, Michael Tjernström and Erland Källén*	Rune G. Graversen
A1.4	The Nordic Seas: Observed Changes *Svein Østerhus and Tore Furevik*	Svein Østerhus
A1.5	Fluctuations in the East Greenland Current during the Medieval Warm Period and Little Ice Age *Karin G. Jensen, Antoon Kuijpers and Simon R. Troelstra*	Antoon Kuijpers
A1.6	Determining Sea Ice Extent from Ice Core Records *Jocelyne C. Bourgeois, Roy M. Koerner and Bea T. Alt*	Jocelyne C. Bourgeois
A1.7	Russian Arctic Meteorological Dataset for ACIA Program Development *V.E Lagun*	V.E Lagun
A1.8	The Analysis of Climatic Changes of Southwest Yakutia for the Centenary Period *Olga Yu. Rozhkova*	Olga Yu. Rozhkova
A1.9	History of Sea Ice in Icelandic waters *Thor Edward Jakobsson*	Thor Edward Jakobsson

Poster Presentations: Past, Present and Future Changes in Biological Systems

A2.1	Structure of the Plant Communities of Spruce Open Woodland of Different Ages on the Taiga-Tundra Boundary in the East European Part of Russia *Adrian E. Katenin*	Adrian E. Katenin
A2.2	Environmental Changes in the North Atlantic Region: SCANNET as a Collaborative Approach for Documenting, Understanding and Predicting Changes *T.V. Callaghan, M. Johansson, O.W. Heal, N. R. Sælthun, L.J. Barkved, N. Bayfield, O. Brandt, R. Brooker, H.H. Christiansen, M. Forchhammer, T.T. Høye, O. Humlum, A. Järvinen, C. Jonasson, J. Kohler, B. Magnusson, H. Meltofte, L. Mortensen, S. Neuvonen, I. Pearce, M. Rasch, L. Turner, B. Hasholt, E. Huhta, E. Leskinen, N. Nielsen and P. Siikamäki*	T.V. Callaghan
A2.3	UV Irradiation of Tundra Soil Microorganisms Varies with Plant Cover *Kevin A. Hughes, Kerstin Scherer, Trond Svenøe, Petra Rettberg, Gerda Horneck and Pete Convey*	Kevin A. Hughes
A2.4	The Effect of Climatic Change on Growth of Sub-arctic Birch Woodlands in Iceland *Thorbergur H. Jónsson*	Thorbergur H. Jónsson
A2.5	The Distribution Areas of Mountain Birch in the North Atlantic Region May Respond Differently to Climatic Warming than Cooling of the Climates *Thorbergur H. Jónsson*	Thorbergur H. Jónsson
A2.6	The Bering Sea is Shifting from an Arctic Ecosystem to a Subarctic Ecosystem *James E. Overland, Jennifer Boldt, Phyllis J. Stabeno and S. Lyn McNutt*	James E. Overland
A2.7	Bioclimatic mapping in Finnmark, Northern Norway, using Landsat TM/ETM+ land cover data *Bernt Johansen, Stein Rune Karlsen, and Arve Elvebakk*	Stein Rune Karlsen
A2.8	Life History Traits of Arctic Charr and Environmental Factors: Local Variability and Latitudinal Gradients *Hilmar J. Malmquist*	Hilmar J. Malmquist
A2.9	The Problem of Study and Preservation of Bioresources of Reserves in the Russian Far East *Ludmila A. Melnikova*	Ludmila A. Melnikova

A2.10	Using Integrated Management and GIS Analysis to Understand Impacts and Adaptation to Climate Change for Fish and Marine Mammals in the Canadian Beaufort Sea *Magdalena A K Muir and Jennifer A Shea*	Magdalena A K Muir
A2.11	Using Migration Counts from Eastern Canada to Assess Productivity of Arctic-breeding Shorebirds in Relation to Climate *R. I. Guy Morrison*	R. I. Guy Morrison
A2.12	Long-Term UV-B Exposure Study on Peatland Ecosystem in Northern Finland *Mörsky, S., Haapala, J., Rinnan, R., Saarnio, S., Silvola, J., Martikainen, P.J. and Holopainen, T.*	S. Mörsky
A2.13	The Influence of UVB Radiation on Lake Ecosystems of the Canadian High Arctic *Sofia L. Perin and David R.S. Lean*	Sofia L. Perin
A2.14	Intense Feeding of *Calanus hyperboreus* on Arctic Autumn Bloom Propagated by a Record Minimum Sea Ice Extent in 2004 *Stig Falk-Petersen, Anette Wold, Anders Røstad, Eva Leu, Henrik Nygård, Bjørn Gulliksen, Jørgen Berge, Essi Keskinen, Jonas Gjaldbæk Thormar and Slawomir Kwasniewski*	Stig Falk-Petersen
A2.15	Sustainable Use of Mountain Birch Forests in a Changed Climate *Oddvar Skre, Kari M. Laine, Frans E. Wielgolaski, Staffan Karlsson, Seppo Neuvonen, Alison Hester, Dietbert Thannheiser, Hans Tømmervik and Soffia Arnthorsdottir*	Kari M. Laine
A2.16	UV Radiation and Photoprotective Pigments in Scots Pine Saplings (*Pinus sylvestris* L.) *Minna Turunen, Francoise Martz, Marja-Liisa Sutinen, Kirsti Derome, Satu Huttunen, Gunnar Wingsle, Riitta Julkunen-Tiitto, Kaisa Lakkala*	Minna Turunen
A2.17	UV-B Radiation and Timberline Plants *Minna Turunen and Kirsi Latola*	Minna Turunen
A2.18	Influence of Climatic Factors on the Nitrogen Fixation Activity in High Arctic Vegetation *Matthias Zielke, Rolf A. Olsen, and Bjørn Solheim*	Matthias Zielke
A2.19	Climate-Driven Regime Shifts in Arctic Lake Ecosystems *Atte Korhola, Sanna Sorvari, John P. Smol, Alexander P. Wolfe, H. John B. Birks, Marianne S.V. Douglas, Vivienne J. Jones, Reinhard Pienitz, Kathleen Rühland, Dermot Antoniades, Stephen J. Brooks, Marie-Andrée Fallu, Mike Hughes, Bronwyn Keatley, Tamsin Laing, Neal Michelutti, Larisa Nazarova, Marjut Nyman, Andrew M. Paterson, Bianca Perren, Roberto Quinlan, Milla Rautio, Émilie Saulnier-Talbot, Susanna Siitonen, Nadia Solovieva and Jan Weckström*	Atte Korhola
A2.20	Climate Change and Tree Line Dynamics in Northwest Siberia: Tree Ring Reconstruction for the Last 7000 Years *Rashit M. Hantemirov and Alexander Y. Surkov*	L. Agafonov
A2.21	The Tundra-Taiga Interface *Terry V. Callaghan, Robert M.M. Crawford, Annika Hofgaard, Matti Eronen, Serge Payette, Gareth Rees, Oddvar Skre, Bjartmar Sveinbjörnsson and Tatiana Vlassova*	Bjartmar Sveinbjörnsson
A2.22	Some Correlation the High Rate of Mortality of the Sea Otter's Population with Average Sunspot Numbers, Volcanic Activity and Natural Regulation at Some Part of the Pacific Ecosystem *Konstantin Sidorov, Mihail Pereladov and Vladimir Sevostianov*	

Poster Session B: Thursday 11 November

Poster Presentations: Possible Feedbacks on the Global Climate System

B3.1	Russian Arctic Methane Fluxes Study: Measurements and Modelling *Jagovkina S.V., Karol I.L., Reshetnikov A.I., Paramonova N.N., Lagun V.E.*	S.V Jagovkina
B3.2	Arctic Sea Ice, Climate Change and Related Climate Feedback Mechanisms *S. Gerland, D.K. Perovich, J. Haapala, I. Harms, B.V. Ivanov, C.A. Pedersen, C. Haas, E. Hansen, M.J. Karcher, G. Magnusdottir, M.G. McPhee, J. Morison, J-G. Winther and B. Njåstad*	S. Gerland

B3.3	Estimation of the Carbon Cycle in Forest Ecosystems of the Pechora River Basin (Northeast European Russia) *Bobkova K., Tuzhilkina V., Galenko E. and Kuzin S.*	P. Kuhry
B3.4	Carbon Sequestration of East European Tundra Landscape *Juha E.P. Heikkinen and Pertti J. Martikainen*	P. Kuhry
B3.5	The Runoff and Concentrations of Nutrients in the Rivers Utsjoki (N. Finland) and Khosedayu (N.E. European Russia) *Eeva-K Huitu and Lauri M. Arvola*	P. Kuhry
B3.6	Soil Carbon Database for the Usa River Basin, Northeast European Russia *G. Mazhitova, P. Kuhry and T. Virtanen*	P. Kuhry
B3.7	Modelling Treeline and Phytomass Changes in European Arctic Catchments *Tarmo Virtanen, Kari Mikkola and Ari Nikula*	P. Kuhry
B3.8	Spatial Variability of Atmospheric DMS and its Implication of Cloud Formation in the High Arctic -A Model Study *Jenny Mattsson, Caroline Leck and Gunilla Svensson*	Jenny Mattsson
Poster Presentations: Impacts on Wildlife and Conservation / Policy issues		
B4.1	The Combined Effects of Climate Change, Acid Rain and Ultraviolet Radiation (UVR) on Mercury Contamination of Arctic Ecosystems *David Lean, Nazafarin Lahoutifard, Sofia Perin, Melissa Sparling, Lisa Loseto, Susannah Scott, Parisa Ariya, Marc Amyot Steven Siciliano and Nelson O'Driscoll*	David Lean
B4.2	Lead-210 Concentration in Ground-Level Air in Finland – Correlation with the State of the North Atlantic Ocean *J. Paatero, J. Hatakka, R. Mattsson, V. Aaltonen and Y. Viisanen*	J. Paatero
B4.3	Evidence and Implications of Dangerous Climate Change in the Arctic *Lynn D. Rosentrater, Mark New, Jed O. Kaplan, Josefino C. Comiso, Sheila Watt-Cloutier, Terry Fenge, Paul Crowley, and Tonje Folkestad*	Tonje Folkstad
B4.4	Heavy Metals and Persistent Organic Pollutants in Air and Precipitation in Iceland *Elin B. Jonasdottir and Johanna M. Thorlacius*	Elin B. Jonasdottir
B4.5	Global Emission Estimates for GHG within the EU EVERGREEN project (EnVisat for Environmental Regulation of GREENhouse gases) *J.M. Pacyna, S. Mano, A. Luekewille, D. Panasiuk, S. Wilson and F. Steenhuisen*	F. Steenhuisen
Poster Presentations: Impacts on Human Activities		
B6.1	Storms and Coastal Impacts in the Mackenzie Delta Region of the Beaufort Sea, Northwest Territories and Yukon, Canada *Steven Solomon, Gavin Manson, David Atkinson, Don Forbes*	Steven Solomon
B6.2	The Economic Implications of a Shortened Winter Exploration Season on the North Slope of Alaska *Sherri L. Wall*	Sherri L. Wall
Poster Presentations: Arctic-Global Connections and Assessing Impacts of Change		
B7.1	Climate Change Research at the Royal Swedish Academy of Sciences Abisko Scientific Research Station, Northernmost Sweden Terry V. Callaghan, Christer Jonasson, Torben R. Christensen and Margareta Johansson	Terry V. Callaghan
B7.2	ITEX in Iceland: Responses of Two Contrasting Plant Communities to Experimental Warming *Borgþór Magnússon, Ingibjörg Svala Jónsdóttir, Jón Guðmundsson and Hreinn Hjartarson*	Borgþór Magnússon
B7.3	Freshwater Ecosystems and Global Change: A Brief Introduction to EURO-LIMPACS *Jón S. Ólafsson*	Jón S. Ólafsson
B7.4	Zackenberg Basic: Monitoring of Ecosystem Dynamics in High-Arctic Northeast Greenland *Morten Rasch, Birger U. Hansen, Hans Meltofte, Dorthe Petersen, Søren Rysgaard, Mikkel P. Tamstorf*	Morten Rasch

B7.5	Recent Progress towards Establishing an Arctic Ocean Observing System: A NOAA Contribution to the Study of Environmental Arctic Change (SEARCH) *Ignatius G. Rigor, Jacqueline A. Richter-Menge and John Calder*	Ignatius G. Rigor
B7.6	Global Terrestrial Network for Permafrost (GTN-P) – A Contribution to Improved Understanding of the Arctic Climate System *S.L. Smith, M.M. Burgess, V. Romanovsky, G.D. Clow, F.E. Nelson, J. Brown*	S.L. Smith
B7.7	Arctic Change Detection in the Post-ACIA Period *Nancy N. Soreide, John Calder, James E. Overland and Florence Fetterer*	Nancy N. Soreide
B7.8	The Swedish Icebreaker Oden as a Research Platform: The Arctic Ocean Experiment 2001 *Michael Tjernström and Caroline Leck*	Michael Tjernström
B7.9	Development of the Archive of Historical Ice Charts of the Arctic Region for the XX Century and Statistical Parameters Describing Variability of Ice Conditions *V.M. Smoljanitsky*	V.M. Smoljanitsky
B7.10	The AARI Oceanographic Database and Its Use in Investigations of the Arctic Ocean *V.T. Sokolov, V.Yu Karpiy and N.V. Lebedev*	V.T.Sokolov
B7.11	Climate Change in the Arctic: Information Support of the Problem *V. Rykova*	
	Poster Presentations: Past, Present and Future Changes in Social Systems	
B8.1	Climate Change and Health among Women of Labrador *Sandra Owens and Christopher Furgal*	Christopher Furgal
B8.2	Interactive Poster – "When the Weather is Uggianaqtuq: Inuit Observations of Environmental Change" *Shari Fox Gearheard and Inuit from the communities of Baker Lake and Clyde River, Nunavut*	Shari Fox Gearheard
B8.3	Climatic Changes Associated with Societal Changes Produce New Combination of their Direct Impacts on Health *Juhani Hassi*	Juhani Hassi
B8.4	Impacts of Climate Change on the Health of Northern Indigenous People (see Session 8 abstract) *Keith Maguire and C. Dickson*	

* Provisional

The Arctic Climate: – Past and Present (ACIA Chapter 2)

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1. Introduction

This paper will present an analysis of the Arctic climate over the past century. The emphasis will be on changes in land-surface temperatures. The paper is based on Chapter 2 of the Arctic Climate Impact Assessment (McBean, et al., 2004).

2. Methods

All Arctic countries maintain programs of synoptic observations to support their economic activity and the sustainability of communities in the Arctic. Arctic systematic *in-situ* meteorological observations started in the late 18th century in the Atlantic sector and in other sectors later. In terms of the circum-Arctic region, only for the last 50 years or so has there been adequate (but not good) coverage. The observational base for Arctic climate is quite limited with few long-term stations and a paucity of observations in general, making it difficult to distinguish with confidence between the signals of climate variability and change. For this study, the focus has been on land surface stations for the Arctic, defined arbitrarily as north of 60^{o}N. For discussions of atmospheric pressure, analyzed fields over the entire Arctic have been used.

In developing data sets for climate analysis, there are different levels of quality assurance, data infilling and homogenization adjustments of these datasets. Consequently, temperature trends using the Climatic Research Unit database (CRU)(Jones and Moberg, 2003) and the Global Historical Climatology Network database (GHCN)(updated from Peterson and Vose, 1997) have been compared. Both databases were employed in the IPCC Third Assessment Report (2001c, Section 2.2.2) to summarize the patterns of temperature change on global land areas since the late 19th century.

3. Results

The CRU time series of annual land-surface air temperature variations in the Arctic (north of 60^{o}N) from 1900-2002 is virtually identical to the GHCN (Figure 1). During that period, there is a statistically significant warming trend of 0.09 ºC decade^{-1}. This Arctic trend is more than the 0.06 ºC decade^{-1} increase averaged over the Northern Hemisphere (IPCC 2001b, p.152). In general, temperature increased from 1900 to the mid-1940s, then decreased until about the mid-1960s, and increased again thereafter. For the period, 1966-2002, the average over the region was 0.38 ºC decade^{-1}, approximately 4 times greater than the average for the century. While the changes are most pronounced in winter and spring, all seasons experienced an increase in temperature during the last several decades. The general features of the Arctic time series are similar to those of the global time series, but decadal trends and interannual variability are somewhat larger in the Arctic.

The instrumental record of land-surface air temperature is qualitatively consistent with other climate records in the Arctic (Serreze et al., 2000). For instance, the 'maritime' Arctic (as represented by coastal land stations, drifting ice stations, and Russian North Pole stations) warmed at the rate of 0.05 ºC decade^{-1} during the 20th century (Polyakov et al., 2003b). As with the land-only record, the warming was largest in winter and spring, and there were two relative maxima during the century (the late 1930s and the 1990s). For periods since 1950, there is a similar rate of warming. However, due to the scarcity of data prior to 1945, it is very difficult to say whether the Arctic as a whole was as warm in the 1930-40s as the most recent decade. In the Polyakov et al. (2003) analysis, only coastal stations were chosen and most of the stations contributing to the high values in the 1930s were in Scandinavia. Interior stations, especially those between 60^{o}N (the southern limit for this study) and 62^{o}N (the southern limit for the Polyakov et al. study), have warmed more. Arctic pack-ice extent contracted from 1918 to 1938 and then expanded between 1938 and 1968 (Zakharov 2002). The expansion after 1938 implies that the Arctic was cooling during that period.

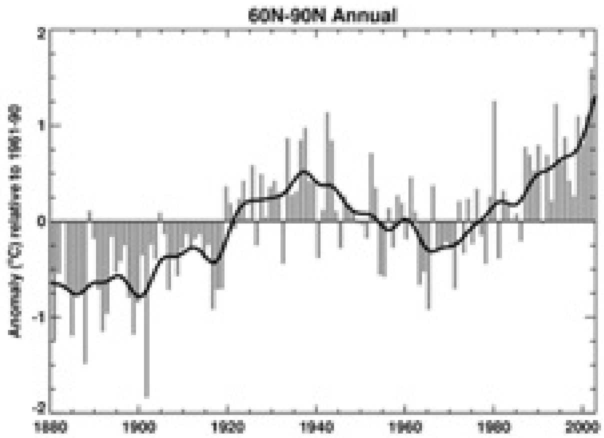

Figure 1: Annual anomalies of land-surface air temperature (^{o}C) from 60^{o}N-90^{o}N for the period 1980-2002, using the GHCN time series (updated from Peterson and Vose, 1997). Anomalies are relative to a 1961-90 base period. The smoothed curve was created using a 21-point binomial filter giving near decadal averages.

For comparison purposes, the temperature trends (in ^{o}C yr^{-1}) for the land-surface temperatures (GHCN database) were computed for the latitude bands 60N-90N and Equator-60N (Figure 2). For the 60^{o}N-90^{o}N band, the trend over any period from the present back to 120 years is positive (i.e., the Arctic is warming). For the 0-60^{o}N band, the trend is also always positive. Although the trends for both bands have been increasing over the past 60 years, the trend for 60^{o}N-90^{o}N is larger. The rate of warming in the Arctic (as defined here) exceeds that of lower latitudes. Due to natural variability and sparse data in the Arctic, the Arctic trend shows more variability and the confidence limits are wider. Over the past 40 years, the Arctic warming is about 0.4 ^{o}C decade^{-1} compared to 0.25 ^{o}C decade^{-1} for the lower latitudes.

Likewise, satellite thermal infrared data on surface temperature, which provides pan-Arctic coverage from 1981-2001, exhibited statistically significant warming trends in all areas between 60^{o}N-90^{o}N except Greenland (Comiso, 2003). The warming trends were 0.33 ºC decade^{-1} over the sea ice, 0.50 ºC decade^{-1} over Eurasia and 1.06 ºC decade^{-1} over North America. In addition, the recent reduction in sea ice thickness (Rothrock et al., 1999), the retreat of sea ice cover (Parkinson et al., 1999), and the decline in perennial ice cover (Comiso, 2002) are consistent with large-scale warming in the Arctic.

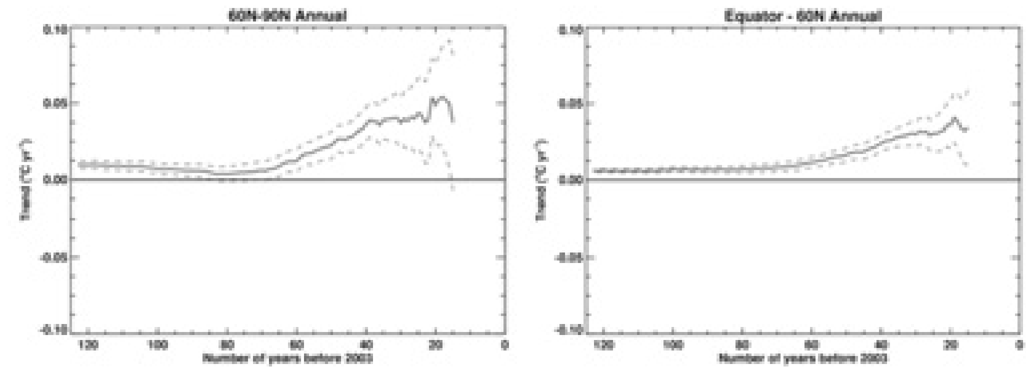

Figure 2: Temperature trends (in ºC yr^{-1}) for land-surface temperatures (GHCN database) (solid lines) and 95% significance levels (dashed lines) based on the period from present to 120 years before present. Hence, the value corresponding to 60 years before present is the average trend for the period 1944-2003.

4. Conclusions

Based on the analysis of the climate of the 20th century, it is concluded that the Arctic has *very likely* warmed up over the past century, although the warming has not been uniform. The average surface temperature for land stations north of 60ºN increased approximately 0.09ºC $decade^{-1}$ over the past century, more than the 0.06 ºC $decade^{-1}$ increase averaged over the Northern Hemisphere. The rate of change has increased over the past 4 decades and is higher than that for the regions 0-60ºN. The paper will also examine the evidence for polar amplification, which depends on the time scale of examination.

Other analyses presented in the ACIA Chapter 2, lead to the following additional conclusions. While atmospheric pressure over the Arctic basin has *very likely* been dropping, it is *likely* that there has been an increase in total precipitation at the rate of about 1% $decade^{-1}$ over the past century. Trends in precipitation are hard to assess because it is difficult to measure with precision in the cold Arctic environment. Snow cover extent around the periphery of the Arctic has *very likely* decreased. There *very likely* have also been decreases in sea ice extent averaged over Arctic over at least the last 40 years and *very likely* a decrease multi-year ice extent in central Arctic.

Reconstruction of the Arctic climate over thousands to millions of years demonstrates that the Arctic climate can vary by large amounts. There appears to be no natural impediment to human-induced climate change being very large (and much larger in the Arctic than the change on the global scale). The variability and transitions have been rapid, from a few to several degrees over a century.

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Indigenous Perspectives on the Changing Arctic (ACIA Chapter 3)

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Chapter Summary

Indigenous peoples in the Arctic have for millennia depended on and adapted to their environment. Their knowledge of their surroundings is a vital resource for their well-being. Their knowledge is also a rich source of information for others who wish to understand the Arctic system. In the context of climate change, indigenous observations and perspectives offer great insight not only into the nature and extent of environmental change, but also into the significance of those changes for the peoples whose cultures are built on an intimate connection with the Arctic landscape.

Chapter 3 of the ACIA reviews the concept of indigenous knowledge, summarizes indigenous observations of environmental and climate change that have been documented to date, and presents a series of case studies, largely from hunting and herding societies, examining the perspectives of specific communities or peoples. The case studies are idiosyncratic, but they have in common the intent of conveying the sense of how climate change is seen, not in aggregate statistics or general trends, but in specific details for particular individuals and communities. The case studies set the stage for a discussion of resilience, or protecting options to increase the capacity of Arctic societies to deal with future change, and a review of further research needs.

The observations and case studies in the Indigenous Perspectives chapter contain some common themes. One such observation is that the weather has become more variable and thus less predictable by traditional means. Social changes, such as less time spent on the land, may influence this observation, but there are climatological implications worthy of further exploration. In terms of perceptions of the significance of climate change, there are few, if any, areas where climate change is regarded as the most pressing problem being faced. Nonetheless, most Arctic residents are aware of it, have experience with the types of changes that are being seen and are anticipated, and are concerned about what it will mean for them, their communities, and the future.

Several general conclusions drawn from the chapter are likely to be applicable to all communities affected by climate change, whether the impacts are on balance beneficial or harmful. Climate change is not an isolated phenomenon, but one that is connected to the web of activities and life surrounding Arctic peoples. Thus, it must be understood and assessed in terms of how it interacts with other phenomena and societal and environmental changes taking place. Responses to climate change will not be effective unless they reflect the particular circumstances of each place. Increasing resilience is a useful way to consider the merits of various response options, which are best developed and evaluated iteratively to promote adjustment and improvement as experience and knowledge increase. Indigenous perspectives on climate change offer an important starting point for collaborative development of effective responses.

Symposium Presentation

Chapter 3 of the ACIA, "Indigenous Perspectives on the Changing Arctic", summarizes and synthesizes available information of indigenous observations of climate change from around the circumpolar North. This presentation provides an overview of the chapter, exploring how local and individual approaches to understanding climate change help to create a more complete picture of Arctic change. Examples from chapter case studies that document indigenous observations in different Arctic regions will be presented. The presentation will also explore how indigenous observations contribute to understanding climate change through detecting changes, identifying the implications of those changes, recognizing the many interactions involving specific changes, and understanding the impacts to individuals and communities.

> *We cannot change nature, our past, and other people for that matter, but we can control our own thoughts and actions and participate in global efforts to cope with these global climate changes. That I think is the most empowering thing we can do as individuals.*
>
> George Noongwook, St. Lawrence Island Yupik, Savoonga, Alaska (Noongwook 2000)

Acknowledgements

Many thanks to all of the indigenous peoples around the Arctic who are working to share their observations, experiences and responses to climate change. Thanks to the contributing and consulting authors for this chapter, and to those who provided case studies. Thank you to the ACIA for supporting our work and helping to raise awareness of indigenous perspectives on climate change.

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Future Changes of Climate: Modelling and Scenarios for the Arctic Region (ACIA Chapter 4)

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Increased levels of atmospheric greenhouse gases (GHG) will have a larger effect on climate in the Arctic region than anywhere else on the globe. To estimate a possible future climate change we use physically based, global coupled atmosphere-land-ocean climate models. Given a change in GHG concentrations we can calculate the resulting changes in temperature, precipitation, seasonality etc. Future concentrations of GHG and aerosol emissions can be estimated assuming future demographic, socio-economic and technological changes. Within IPCC, a set of emission scenarios has been prepared; in this assessment we choose to use the so called A2 and B2 scenarios. These are in the middle of the range of scenarios provided by the IPCC. Climate projections, using five different global models and comparing with the present climate, show an average warming of 1.4°C in the mid-21st century for both the A2 and the B2 scenarios. Towards the end of the century, the globally averaged warming is 3.5°C and 2.5°C for the A2 and B2 scenarios, respectively. Over the Arctic region the warming is larger: for the region northward of 60°N, by mid-21st century, both scenarios give 2.5°C. By the end of the 21st century, the Arctic warming is 7°C and 5^{e}C for A2 and B2, respectively (Fig. 1). By that time, in the B2 scenario, the annual average warming of around 3ºC is projected for Scandinavia and East Greenland, about 2ºC for Iceland, and up to 5ºC for the Canadian Archipelago and Russian Arctic.

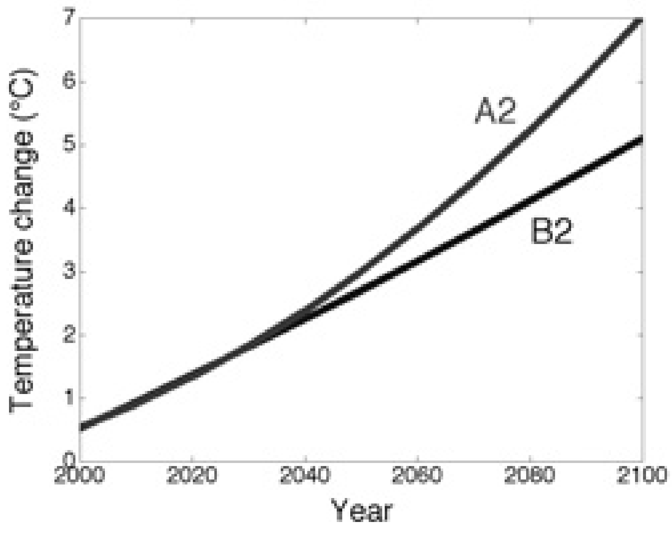

Figure 1. Model-mean A2 and B2 projections of the Arctic (60-90°N) annual mean surface air temperature changes (°C) relative to 1981-2000. A binomial approximation is applied to the original model means.

The model mean warming over the central Arctic Ocean is largest in autumn and winter (for the B2 scenario – up to 9ºC by late-21st century), when the air temperature reacts strongly to reduced ice cover and thickness. Average autumn and winter temperatures are projected to rise by 3-5ºC over most Arctic land areas. By contrast, the warming in summer remains below 1ºC. A contrast between larger warming in autumn and winter and smaller warming in summer also extends to the surrounding land areas but is less pronounced there. In summer (winter), the warming over northern Eurasia and northern North America is larger (smaller) than that over the Arctic Ocean. All of the models suggest substantially smaller warming over the northern North Atlantic sector than in the other parts of the area.

The simulated precipitation increases in the Arctic, by late 21st century from about 5-10% in the Atlantic sector (5-10%) to locally up to 35% in the high Arctic (for the B2 scenario). Like the temperature increase, the increase in precipitation is also generally largest in autumn and winter and smallest in summer.

Throughout the year, there is a slight decrease in pressure in the polar region. While many impact studies would benefit from projections of wind characteristics and storm tracks in the Arctic, the available analysis from the literature are insufficient to justify any firm conclusions on their possible changes in the 21st century.

The models also show a substantial decrease of snow and sea-ice cover over most parts of the Arctic area by the end of the 21st century.

The Arctic is a region characterized by complex and still insufficiently understood climate processes and feedbacks, contributing to the challenge, which the Arctic posres from the viewpoint of climate modelling. We have identified several weaknesses of the models in high-latitude surface process descriptions and we find this to be among most serious shortcomings in present day Arctic climate modelling. Simulation deficiencies are partly due to a coarse model resolution. Additionally, many model formulations are based on low latitude observations that do not cover the extreme climatic conditions occurring in the Arctic. A consequence is a larger spread for model results from the Arctic area (Fig.2) than for results from lower latitudes.

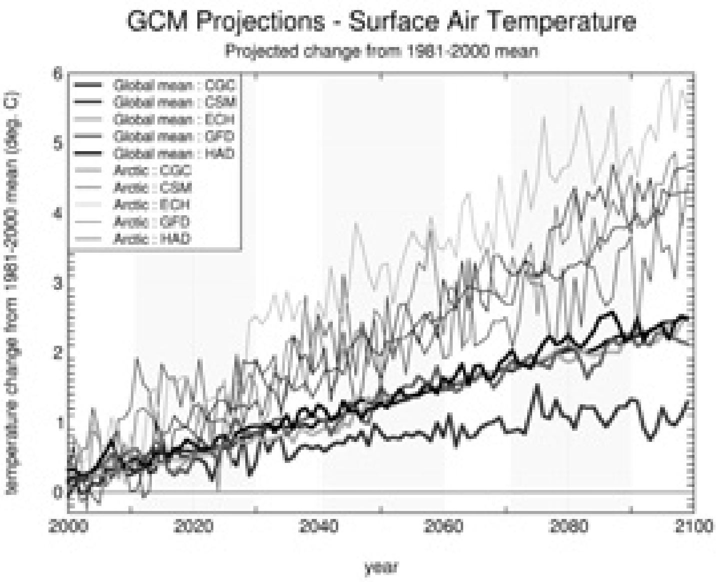

Figure 2. Global (thick lines) and Arctic (60-90°N, thin lines) change in the annual mean surface air temperature relative to the baseline period 1981-2000 (ºC) in the 5 individual ACIA B2 projections.

Local and regional climate features, such as enhanced precipitation close to steep mountains, are not well represented in global climate models due to their limited horizontal resolution. To describe local climate, we can either use statistically based empirical links between the large-scale flow and local climate or physical modelling. A local climate change can more easily be translated into impacts than a direct use of global model results. Physically based methods for local and regional climate simulation rely on high resolution models run over limited time slices. One alternative is to use a high resolution global stand-alone atmospheric model driven with ocean surface conditions simulated in a coarser resolution coupled model. Another alternative is a regional model with an increased horizontal resolution, driven at the lateral boundaries with coarser resolution global model output. All methods can be used to interpret global simulations on finer scales and capture areas with intensified precipitation, extreme wind events etc. Unfortunately, high-resolution global model results for the Arctic have not been available for this assessment. In spite of fast developments in the Arctic regional climate modelling, its current status does not allow regional models to be employed as principal tools for ACIA. Thus the main possibility for ACIA is to use coupled global models' projections either directly or in combination with statistical downscaling techniques.

A model simulation gives us one possible climate scenario. This is not a prediction of future climate, we can only calculate the climate change based on a prescribed change in atmospheric GHGs. A climate shift can be due to natural variability as well as a GHG induced change. Natural variability in the Arctic is large and could mask or amplify a change due to human activities. This effect could be larger or smaller depending on the region, the climate parameter (temperature, precipitation, snow cover etc) and the time and space scales. To assess the relative importance of natural variability versus a prescribed climate forcing an ensemble of differently formulated climate models should be used. This technique requires substantial computing resources; here we use only five different models to give an indication of simulation uncertainty versus forced changes. Ensembles containing on the order of hundred simulations would give a better estimate of climate change probability distributions. We would also have a possibility to estimate changes in the frequency of winter storms, temperature and precipitation extremes, etc.

While we believe that the level of uncertainty in climate simulations can be lowered with improved model formulations, we can never be certain that all physical processes relevant to climate change have been included in a model simulation. There can still be surprises to come in our understanding of climate change. Our present estimates are based on the best knowledge available today about climate change; as climate change science progresses there will always be new results that can change our understanding of how the Arctic climate system works.

Ozone and Ultraviolet Radiation (ACIA Chapter 5)

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Introduction

The ozone depletion observed over the Arctic during the past twenty years has reduced normally high winter and springtime ozone amounts, potentially allowing more ultraviolet (UV) radiation to reach the Earth's surface. Ozone loss over the Arctic has been of similar magnitude to that over the Antarctic (Figure 1). Observations have shown substantial late winter and early springtime column ozone reductions in the Arctic over the last two decades. These reductions have been directly tied to chemical losses occurring at low temperatures in the presence of human-produced chlorine and bromine compounds. The year-round ozone trend over the Arctic for 1979-2000 has been about -3% per decade with accumulated losses of approximately 7%. The springtime ozone trend has been about -5% per decade. Accumulated springtime total ozone losses are approximately 11%.

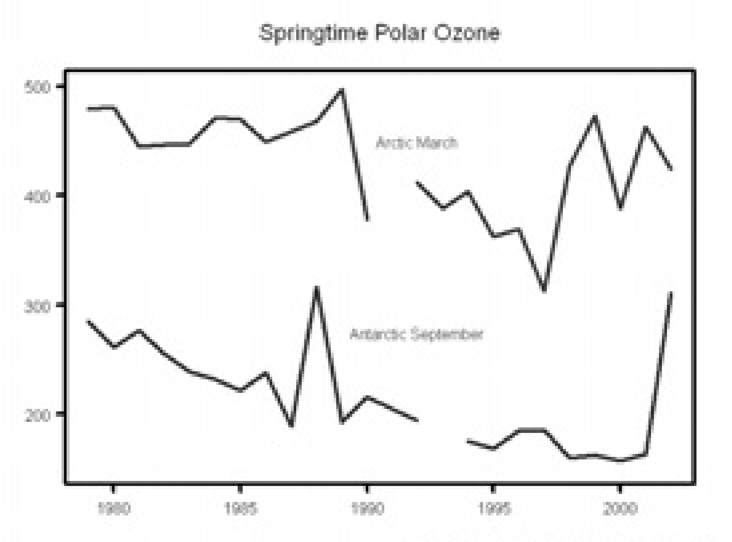

Figure 1. Springtime ozone depletion over the Antarctic and the Arctic. Substantial depletion has occurred over both poles, and depletion has been similar in magnitude, though not in percent loss, over each region.

Ozone in the stratosphere absorbs radiation at UV wavelengths and therefore directly influences the amount of UV radiation reaching the Earth's surface. Surface UV levels are also strongly affected by clouds, aerosols, altitude, solar zenith angle, and surface albedo. These different factors contribute to high variability in UV levels and make it difficult to identify clear UV changes resulting from ozone depletion. Because of the low solar elevation in the Arctic, the region is subject to an increased proportion of diffuse UV radiation, from scattering in the atmosphere as well as from reflectance off snow and ice. Reflectance off snow can increase the biologically effective irradiance by over 50%. Understanding changes in UV doses has important implications for human and ecosystem health. UV exposure has been linked to skin cancers, corneal damage, cataracts, immune suppression, and aging of the skin in humans, and can also have deleterious effects on ecosystems and on materials.

Changes in global climate are likely to result in changing snow cover and sea ice in the Arctic, affecting the UV exposure of various ecosystems. Both snow and ice cover have strong attenuating effects on UV, protecting organisms underneath. A reduction in snow and ice cover on the surface of rivers, lakes, or oceans may increase exposure of many organisms to damaging UV. Loss of snow or ice cover earlier in the season when UV radiation may be at increased levels could be stressful for both aquatic and terrestrial life.

Monitoring Arctic Ozone and UV

Ground-based and satellite instruments are used to monitor the amounts and profiles of stratospheric ozone. Currently, over 30 Dobson and Brewer instruments are operated in or near the Arctic. Some of these records date back to the 1920s. The vertical ozone distribution can also be measured using ozone sondes. The available data have been used in many analyses of ozone depletion and indicate strong downward trends in stratospheric ozone amounts, particularly during the late winter and spring. Ozone amounts also show strong latitudinal variations as well as notable longitudinal variations.

Ground-based instruments measure UV levels in all eight Arctic countries, though the amount of coverage varies with the region. Surface UV amounts can also be inferred from satellite data. Available individual measurements suggest localized increases in UV levels reaching the surface, but so far the measurement time series are not long enough to allow upward trends in UV to be detected. Reconstructed surface UV time series based on total ozone, sunshine duration, and cloud cover suggest distinct UV increases, but reconstruction methods are less certain than direct measurements because they involve assumptions about the spectral characteristics of cloud and aerosol attenuation and surface reflectivity. The increases in UV have been found to occur mainly in the springtime, during the maximum ozone depletion. This increase can result in springtime UV levels that can be higher than those measured during the summer.

Future Arctic Ozone and UV Projections

Atmospheric sampling indicates that the Montreal Protocol and its amendments have resulted in a peak and the beginning of a decline in the amounts of some ozone depleting substances. However, climate change and other factors are likely to affect the recovery of the ozone layer. Changes in both the overall meteorology of the region and in atmospheric composition may delay or accelerate the recovery of Arctic ozone. These changes contribute to difficulties in projecting future Arctic ozone amounts. Generally, the two-dimensional (2-d) models compared in the 2002 Ozone Assessment predict local minimums in Arctic ozone in the late 1990s, followed by a slow, gradual increase. Ozone values in 2020 are significantly lower than the 1980 values for all of these 2-d models. Three-dimensional chemistry-models offer greater insight into dynamical factors affecting current and future Arctic ozone levels. Expectations from three chemistry-climate models are shown in Figure 2 and report larger ozone depletion for the Arctic during 1980-2000 than is projected by the 2-d models. The 2015 results from the 3-d models show improvement to levels above those in 1980 but still lower than the 1960 amounts. The only 3-d model to project ozone amounts beyond 2020 predicts only modest recovery in 2045.

Arctic ozone experiences high natural seasonal and interannual variability, driven primarily by the atmospheric dynamics governing the large-scale meridional transport of ozone from the tropics to high latitudes. The large natural variability complicates our ability both to interpret past changes and to predict future ozone levels. Confounding matters further, stratospheric temperatures and polar stratospheric cloud formation also affect Arctic ozone depletion. Climate changes leading to lower temperatures in the stratosphere are likely to increase the frequency and severity of ozone depletion episodes. Overall, ozone levels are expected to remain depleted for several decades and thus UV levels over the Arctic are likely to remain elevated in the coming years. The elevated levels will likely be most pronounced in the springtime when ecosystems are most sensitive to harmful UV.

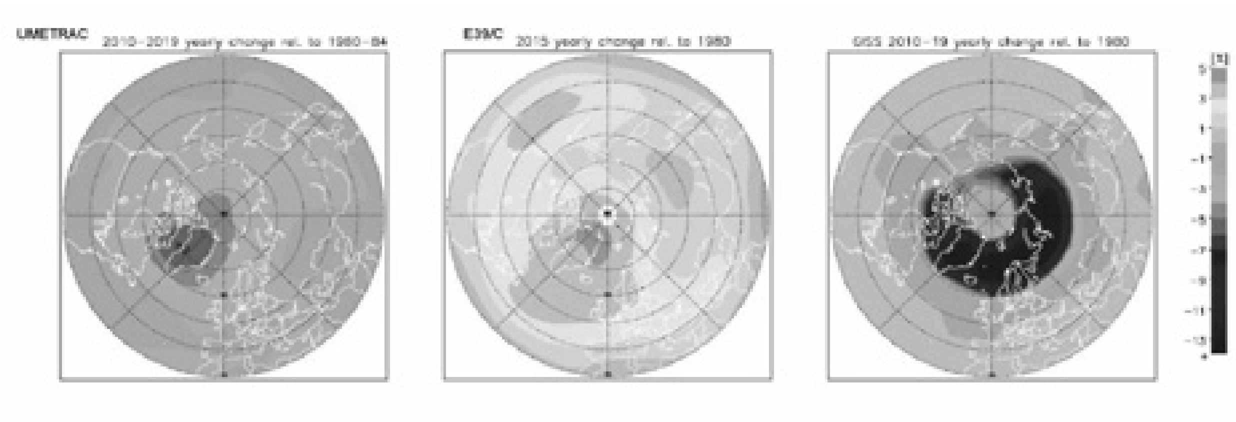

Figure 2. 3-d model projections of changes in the yearly average column ozone for the period 2010-2019 relative to the model results for 1980. (a) UMETRAC, change calculated relative to 1980-1984; (b) E39/C, projected change for 2015; (c) GISS, change relative to 1980.

Cryospheric and Hydrologic Variability (ACIA Chapter 6)

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Recent observational data present a generally consistent picture of cryospheric variations that are shaped by patterns of recent warming and variations of the atmospheric circulation. While the various cryospheric and atmospheric changes are consistent in an aggregate sense and are quite large in some cases, it is likely that low-frequency variations in the atmosphere and ocean have played at least some role in forcing the cryospheric and hydrologic trends of the past few decades. Model projections of greenhouse-driven warming indicate a continuation of the recent trends through the next century, although the rates of the projected changes vary widely among the models.

Sea ice coverage has decreased by 5-10% during the past few decades. The decrease is greater in the summer, when new period-of-record minima have been reached several times in the most recent decade. The coverage of multiyear ice has also decreased, as has the thickness of sea ice in the central Arctic. Models project a 21st-century decrease of sea ice by more than 50% in the summer season, with a corresponding lengthening by 2-4 months of the navigation season in the Northern Sea Route. Other impacts of the reduced sea ice cover will be a larger fetch for wave generation by storm systems, increased vulnerability of coastlines now protected by sea ice for at least part of the year, and an increase in the availability of oceanic moisture for the atmosphere.

Snow-covered area has diminished since the early 1970s by several percent over both North America and Eurasia, although most of the decrease occurred during a period of several years in the late 1980s. Snow cover is projected to continue to decrease, with the largest decreases projected for spring and autumn. If such changes occur, the snow season will be shortened and the growing season will lengthen. The springtime pulse of runoff is likely to occur earlier, raising the possibility of drier land areas during summer if precipitation does not increase.

Glaciers throughout much of the Northern Hemisphere have lost mass over the past several decades, as have coastal regions of the Greenland ice sheet. The cumulative loss of mass since 1960 from glaciers in the North American Arctic is nearly 500 cubic kilometers. The glacier retreat has been especially large in Alaska since the mid-1990s. During the past decade, glacier melt has resulted in an estimated sea level increase of 0.15-0.30 mm/year. The wastage of arctic glaciers and the Greenland ice sheet is projected to contribute several additional cm to global sea level rise by 2100. Superimposed on the glacial contributions to sea level change are the effects of thermal expansion and isostatic rebound, which combine to produce a spatially variable pattern of sea level rises of several tens of centimeters in some areas (the Beaufort Sea and much of the Siberian coast) and sea level decreases in other areas (e.g., Hudson Bay, Novaya Zemlya).

Permafrost temperatures over most of the subarctic land areas have increased during the past few decades by several tenths °C to as much as 2-3°C. On the basis of the warming projected to occur over the next century, permafrost could begin to thaw over 10-30% of the present permafrost area, and the outer limit of permafrost may move northward by several hundred km. A key uncertainty is the timing of permafrost degradation, defined as the failure of the active layer to completely refreeze during winter, relative to the warming of the surface air temperatures. Whether the permafrost degrades or the active layer thickens, there will be major impacts on the infrastructure, hydrology and ecosystems of the Arctic.

Earlier break-up and later-freeze-up have combined to lengthen the ice-free season of rivers and lakes by 1-3 weeks over the past century in much of the Arctic. The lengthening of the ice- free season has been greatest in the western and central portions of the northern continents. Continued trends toward earlier break-up and later freeze-up of Arctic rivers and lakes are also likely if the projected warming occurs. While these trends point to a longer navigation season, there is also the possibility that summer water levels will decrease during summer if there is a longer post-breakup period during which evapotranspiration exceeds precipitation over the arctic terrestrial watersheds.

River discharge over much of the Arctic has increased during the past several decades, and the springtime discharge pulse is occurring earlier on many rivers. The increase of discharge is consistent with an irregular increase of precipitation over northern land areas. On the basis of the model projections of precipitation and temperature, arctic river discharge may increase by an additional 5-25% by the late 21st century. This increase of discharge has potentially important implications for the Arctic Ocean freshwater budget and stratification, as well as for the export of freshwater to the North Atlantic subpolar seas.

While the changes summarized above have the potential to cause substantial impacts on arctic ecosystems, infrastructure and people, the changes may combine in ways that enhance the impacts. For example, the increase of sea level, the retreat of sea ice and the degradation of coastal permafrost can combine to accelerate the vulnerability of arctic coastal areas to erosion. Similarly, the lengthening of the snow-free season, in combination with warmer temperatures and greater evapotranspiration rates, can lead to a drying of some areas, increasing their vulnerability to disturbance (e.g., fire, insects).

Climate Change and UV-B Impacts on Arctic Tundra and Polar Desert Ecosystems (ACIA Chapter 7)

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Introduction

A general recognition that the Arctic will amplify global climate warming, that UV-B radiation may continue to increase there because of possible delays in the repair of stratospheric ozone, and that the Arctic environment and its peoples are likely to particularly susceptible to such environmental changes stimulated an international assessment of climate change impacts. The Arctic Climate Impacts Assessment (ACIA) is a four year study, culminating in publication of a major scientific report (ACIA, 2004) as well as other products (Callaghan et al., 2004). The present paper focuses on terrestrial ecosystems of the Arctic, from the treeline ecotone to the polar deserts.

The Arctic is generally recognized as a treeless wilderness with cold winters and cool summers. However, definitions of the southern boundary vary according to environmental, geographical or political biases. This assessment focuses on biota (plants, animals and microorganisms) and processes in the region beyond the northern limit of the closed forest (the taiga), but we also include processes South of this boundary that affect ecosystems in the Arctic.

Arctic ecosystems are expected to be vulnerable to the dramatic environmental changes that the Arctic is experiencing for many reasons. The Arctic is outstanding amongst the biomes of the World in the dominance of climate change amongst the major factors affecting biodiversity. Also, the Arctic biota of the present day are relatively restricted in range and population size compared with their Quaternary history. When the treeline advanced northwards during the warming of the early Holocene, a lowered sea level allowed a belt of tundra to persist around the Arctic basin whereas any future northwards migration of the treeline will further restrict the area of tundra because sea level is expected to rise. Arctic ecosystems are known to be vulnerable to current disturbances and to have long recovery times. Current and predicted environmental changes are likely to add additional stresses and decrease the potential for ecosystem recovery from natural disturbances while providing thresholds for shifts to new states, for example when disturbance opens gaps for invasion of species new to the Arctic.

Changes in Arctic ecosystems and their biota are important to the peoples of the Arctic in terms of food, fuel and culture and potentially could have global impacts because of the many linkages between the Arctic region and those regions further South. Several hundreds of millions of birds migrate to the Arctic each year and their success in the Arctic determines their roles at lower latitudes. Physical and biogeochemical processes in the Arctic affect atmospheric circulation and the climate of regions beyond the Arctic. We know that ecosystems have responded to past environmental changes in the Arctic: we know that current environmental changes are occurring. This understanding indicates that there will be future responses of Arctic ecosystems and species to expected future and ongoing changes in climate. We also know that current levels of UV-B radiation, as well as higher levels, can affect sub-Arctic plants. Arctic plants may be particularly sensitive to increases in UV-B radiation because UV-B damage is not dependent on temperature whereas enzyme-mediated repair of DNA damage could be constrained by low temperatures.

For all these reasons, we need to understand the relationships between ecosystems and the Arctic environment. Although many aspects of the Arctic environment are changing concurrently, for example climate, pollution, atmospheric nitrogen deposition, atmospheric concentrations of carbon dioxide, UV-B radiation and land use, the specific mission of this assessment is to focus on impacts of changes in climate and UV-B radiation on Arctic terrestrial ecosystems and their species and processes.

Our assessment recognizes that the effects of climate are specific to species, age/developmental stages of individuals and processes from metabolism to evolution. We therefore follow a logical hierarchy of increasing organizational biological complexity to assess impacts on species, the structure of ecosystems, the function of ecosystems, and landscape and regional processes. A basic understanding of biological processes related to climate and UV-B radiation is required before we can assess impacts of *changes* in climate and UV-B on terrestrial ecosystems. Consequently, the structure of our assessment progresses from a review of climate and UV controls on biological processes to an assessment of potential impacts of changes in climate and UV-B on processes at the species and regional levels. Some effects of climate change on ecosystems may be beneficial to people, while others maybe harmful.

The changes in climate and UV-B that we use to assess biological impacts are of two types: those already documented and those established from scenarios of UV-B and climate derived from GCMs (Global Climate Models). We assess information on interactions between climate/UV-B radiation and ecosystems based on a wide range of sources derived from experimental manipulations of ecosystems and environments in the field; laboratory experiments; monitoring and observation of biological processes in the field; conceptual modeling using past relationships between climate and biota (paleo analogs), and current relationships between climate and biota in different geographical areas (geographical analogs) to infer future relationships; and process-based mathematical modeling. Where possible, we include indigenous knowledge (limited to published sources) as an additional source of observational evidence.

We recognize that each method has uncertainties and strengths. By considering and comparing different types of information we hope to have achieved a more robust assessment. However, the only certainties of our assessment are that there are various levels of uncertainty with our predictions and that even if we try to estimate the magnitude of these, surprise responses of ecosystems and their species to changes in climate and UV-B radiation are certain to occur.

The key findings of the assessment of climate change impacts on tundra and polar desert ecosystems are listed below and the context in which they were derived is provided in detail in the assessment reports (see Key Publications section).

Key Findings

- The dominant response of current Arctic species to climate change, as in the past, is very likely to be relocation rather than adaptation. Relocation possibilities vary according to region and geographical barriers. Some changes are occurring now.
- Some groups such as mosses, lichens, some herbivores and their predators are at risk in some areas, but productivity and number of species is very likely to increase. Biodiversity

is more at risk in some sub-regions than in others: Beringia has a higher number of threatened plant and animal species than any other ACIA sub region.

- Changes in populations are triggered by trends and extreme events, particularly winter processes.
- Forest is very likely to replace a significant proportion of the tundra and this will have a great effect on the composition of species. However, there are environmental and sociological processes that will probably prevent forest from advancing in some locations.
- Displacement of tundra by forest will lead to a decrease in albedo which increases the positive feedback to the climate system. This positive feedback will generally dominate over the negative feedback of increased carbon sequestration. Forest development will also ameliorate local climate.
- Warming and drying of tundra soils in parts of Alaska have already changed the carbon status of this area from sink to source. Although other areas still maintain their sink status, the number of source areas currently exceeds the sink areas. However, geographical representation of research sites is currently small. Future warming of tundra soils would probably lead to a pulse of trace gases into the atmosphere, particularly in disturbed areas and areas that are drying. It is not known if the circum-Arctic tundra will be a carbon source or sink in the long term, but current models suggest that the tundra will become a weak sink for carbon because of the northward movement of vegetation zones that are more productive than those they displace. Uncertainties are high.
- Rapid climate change that exceeds the ability of species to relocate will very probably lead to increased incidence of fires, disease and pest outbreaks.
- Enhanced CO_2 and UV-B affect plant tissue chemistry and thereby have subtle but long-term impacts on ecosystem processes that reduce nutrient cycling with the potential to decrease productivity and increase or decrease herbivory.

Key Publications

ACIA 2004. Arctic Climate Impact Assessment: Cambridge University Press.

Callaghan, T, V., Björn, L. O., Chernov, Y, Chapin, III. F. S., Christensen, T. R., Huntley, B., Ims, R. A., Johansson, M., Jolly, D., Jonasson, S., Matveyeva, N., Panikov, N., Oechel, W. C., Shaver, G. R. Elster, J., Henttonen, H., Jonsdottir, I. S., Laine, K., Schaphoff, S., Sitch, S., Taulavuori, K., Taulavuori, E. and Zöckler, C. 2004 . Climate Change and UV-B impacts on Arctic Tundra and Polar Desert Ecosystems. *Ambio 33, Number 7, 94 pp.*

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Freshwater Ecosystems (ACIA Chapter 8)

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Introduction

Arctic freshwater ecosystems are particularly vulnerable to climate and UV change impacts. The physical, chemical and biological nature of high-latitude freshwater ecosystems is dominated by pronounced seasonality in weather, the distribution of continuous and discontinuous permafrost, and prominent snow and ice. Widely diverse aquatic biota are well adapted to, and in some instances dependent upon, these environmental variables. Slight changes in temperature and precipitation may result in drastic changes to freshwater ecosystems,. These may occur directly or indirectly through associated terrestrial impacts.

Assessing the impacts of climate change and UV on arctic freshwater ecosystems presents significant challenges. Climate interactions with freshwater systems are complex (Figure 1), as are the potential responses of these diverse systems (i.e., synergistic, cumulative, non-linear, threshold, and feedback effects are likely). Projecting climate change effects on freshwater systems is confounded by a still limited understanding of the structure and function of these systems, but also of the coupling of the climate system to key hydrological and ecological processes.

Figure 1. Interactions between climatic variables, their influence on the biophysical features of freshwater ecosystem habitat, subsequent effects on biological structure and function, and the interaction of feedbacks within and between components.

Given the limited knowledge about aquatic systems, climate change impacts were evaluated using a weight-of-evidence approach. The general hydrological and ecological features of arctic freshwater ecosystems were reviewed, as were historical changes in freshwater systems over the Holocene and recent past. Based on the findings of this historical review and of recent research, the effects of climate change on broad-scale hydro-ecology, ecosystem structure and function, fish, fisheries and aquatic wildlife were assessed. The synergistic effects of effects ultraviolet radiation and contaminants were also addressed.

Key Findings

Changes to runoff and river-ice will alter in-channel, riparian and delta habitats. The most marked impacts will be associated with less pronounced freshet, ice break-up, and flooding as latitudinal temperature gradients decline and as rainfall increases. The effects will include altered channel morphology reflecting a depressed disturbance regime and loss or alteration of riparian, pond and wetland habitats, and reduced species richness and diversity.

Changes to the composition, thickness and duration of ice will also affect freshwater lake habitat. Thermal and radiative regimes of lake waters will very likely shift as ice thins and the ice-free season extends, affecting open water and under-ice habitat. Increased under-ice productivity, rapid spring stratification, reduced circulation, and increased productivity over a lengthened open-water growing season will lead to a loss of habitat as deeper lake waters become increasingly oxygen-depleted. Furthermore, UV damage to organisms and allocation of resources for protection will increase. Changes to timing of freeze-up and melt will affect migratory behavior and reproductive success of some aquatic species.

Changing water levels will also produce important impacts on river, lake and wetland ecosystems. Specifically, rising winter water levels will increase under-ice habitat and affect species abundance and geographic range. Reduced summer water levels due to evaporation and drainage in permafrost degraded landscapes will result in loss of aquatic systems, reduced quality and quantity of aquatic habitat, and promote establishment of terrestrial species. New ponds, wetlands and drainage networks will develop in thermokarst landscapes, creating new habitat and increasing opportunities for the extension of the geographic range of aquatic species northward.

Freshwater habitat and ecosystem productivity will be affected by reductions in permafrost and shifts in vegetation. Productivity will rise and UV exposure decline with increased nutrient, sediment and carbon loading from permafrost-degraded and increasingly vegetated catchments. Enhanced loading of suspended solids may, however, be detrimental to productivity through light-limitation, destruction of aerobic habitat in bottom sediments, and infilling of fish spawning beds.

Degrading permafrost and alteration of vegetation in lake, river and wetland catchments will also affect biogeochemical inputs to and processing within freshwater ecosystems, and the production and consumption of carbon-based gases that may positively feedback to climate change. Biogeochemical cycling will increase as temperatures rise and nutrient- and carbon-enriched runoff from degrading permafrost increases, altering the generation and consumption of trace gases. Though carbon loss from wetlands will likely increase as temperatures rise and soils dry, enhanced vegetation growth will increase carbon sequestration.

The above changes to the physical and biogeochemical nature of arctic freshwater systems will have direct and indirect affects on biodiversity. The magnitude, extent and distribution of these effects will vary with system type and location. This will result in extinctions or loss of certain species, genetic adaptations, alteration of species' ranges and distributions, and increased invasions by southern species. Extension of the geographic range of southern species northward will increase competition for resources and result in increased mortality of northern species due to the introduction of new diseases and parasites. Over time, these effects will likely result in the extirpation of northern species along the southern margins of their geographic ranges.

Changes to the biodiversity and abundance of fishes are of particular relevance to the human population of the Arctic. Likely changes include alteration of species composition with northward migration of southern species, contraction of geographic range of arctic species, and shifts in the balance between migratory (sea-run) and non-migratory (freshwater) forms of many fish species as inland and nearshore waters change. Species that are wholly northern are most vulnerable to change. As fish species and ranges change, fisheries will have to adapt to ensure sustainable populations of northern fishes; the most northerly will potentially be devastated by complete loss of some species. New opportunities for fisheries may, however, occur.

These effects of climate change will be further compounded by cumulative, synergistic and overarching interactions. Decoupling of environmental cues will probably have significant impacts on population processes and the projected rate and magnitude of climate change will outstrip the capacity of many arctic biota, particularly those that are longer-lived (e.g., fish), to adapt or acclimate. Furthermore, climate interactions with contaminants will exacerbate the detrimental effects of climate change, e.g., increased toxic contaminant loadings from melted permafrost and perennial snow and ice, to aquatic systems.

Marine Systems: The Impact of Climate Change (ACIA Chapter 9)

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Approximately 2/3 of the Arctic Region in the ACIA context is comprised of ocean. The Marine Arctic includes the Arctic Ocean and its adjacent shelf seas, as well as the Nordic Seas, the Labrador Sea and the Bering Sea. From a climate change perspective these areas are very important since processes occurring in the Arctic affect the rate of deep-water formation in the convective regions of the North Atlantic, thereby influencing the ocean circulation across the globe. In addition, global climate modeling studies consistently show the Arctic to be one of the most sensitive regions to climate change.

Not surprisingly, many Arctic life forms, including humans, are directly or indirectly dependent on productivity from the sea. Several physical factors make Arctic marine systems unique from other oceanic regions including: a very high proportion of continental shelves and shallow water; a dramatic seasonality and overall low level of sunlight; extremely low water temperatures; presence of extensive permanent and seasonal ice-cover; and a strong influence from freshwater, coming from rivers and ice melt. Some of these factors represent harsh conditions for many types of marine life. Arctic fauna is young, geologically speaking. Recent glaciations resulted in major losses of biodiversity, and recolonisation has been slow because of the extreme environmental conditions and overall low productivity of the Arctic system. This results in Arctic ecosystems, in a global sense, being “simple”. They are composed largely of specialists that have been able to adapt to the extreme conditions and overall species diversity is low. The high seasonal pulse of summer production in the Arctic, during the period of 24 hours light is particularly pronounced near the ice edge and in shallow seas such as the Barents and Bering Sea. This production attracts seasonal migrants that travel long distances to take advantage of Arctic summers and return to the south to overwinter.

Some of the main conclusions are:

- Large uncertainties in the response of the arctic climate system to climate change arise through poorly quantified feedbacks and thresholds associated with the albedo, the THC, and the uptake of greenhouse gases by the ocean. Since climate models differ in their projections of future change in the pressure fields and hence their associated winds, much uncertainty remains in terms of potential changes in stratification, mixing, and ocean circulation.
- The arctic THC is a critical component of the Atlantic THC. The latest assessment by the Intergovernmental Panel on Climate Change (IPCC) considers a reduction in the Atlantic THC likely, while a complete shutdown is considered unlikely but not impossible. If the arctic THC is reduced, it will affect the global THC and thus the long-term development of the global climate system . Reduction in the global THC may also result in a lower oceanic heat flux to the Arctic. If the THC is reduced, local regions of the Arctic are likely to undergo cooling rather than warming, and the location of ocean fronts may change. The five ACIA-designated models cannot assess the likelihood of these occurrences.
- Most of the present ice-covered arctic areas are very likely to experience reductions in sea-ice extent and thickness, especially in summer. Equally important there will very likely be earlier sea-ice melt and later freeze-up. This is likely to lead to an opening of

navigation routes through the Northwest and Northeast passages for greater periods of the year and thus to increased exploration for reserves of oil and gas, and minerals.

- Decreased sea-ice cover will reduce the overall albedo of the region, which is very likely to result in a positive feedback for global warming.
- Upper water column temperatures are very likely to increase, especially in areas with reduced sea-ice cover.
- The amount of carbon that can be sequestered in the Arctic Ocean will likely increase significantly under scenarios of decreased sea-ice cover, through surface uptake and increased biological production.
- Greenhouse gases (CO_2 and CH_4) stored in permafrost may be released from marine sediments to the atmosphere subsequent to warming, thus initiating a strong positive feedback.
- In areas of reduced sea-ice cover, primary production is very likely to increase, which in turn is likely to increase zooplankton and possibly fish production. Increased cloud cover is likely to have the opposite effect on primary production in areas that are currently ice-free.
- The area occupied by benthic communities of Atlantic and Pacific origin will very likely increase, while areas occupied by colder water species will very likely decrease. Arctic species with a narrow range of temperature preferences, especially long-lived species with late reproduction, are very likely to be the first to disappear. A northward retreat for the arctic benthic fauna may be delayed for the benthic brooders (the reproductive strategy for many dominant polar species), while species producing pelagic larvae, will likely be the first to colonize new areas in the Arctic.
- A reduction in sea-ice extent is very likely to decrease the natural habitat for polar bears, ringed seals, and other ice-dependent species, which is very likely to lead to reductions in the survival of these species. However, increased areas and periods of open water are likely to be favorable for some whale species and the distribution of these species is very likely to move northward.
- Some species of seabird such as little auk and ivory gull are very likely to be negatively affected by the changes predicted to occur within the arctic communities upon which they depend under climate warming, while it is possible that other species will prosper in a warmer Arctic, as long as the populations of small fish and large zooplankton are abundant.
- Increased water temperatures are very likely to lead to a northward shift in the distribution of many species of fish and to changes in the timing of their migration, and to a possible extension of their feeding areas, and to increased growth rates. Increased water temperatures are also likely to lead to the introduction of new species to the Arctic but are unlikely to lead to the extinction of any of the present arctic fish species. Changes in the timing of biological processes will likely affect the overlap of spawning for predators and their prey (match/mismatch).
- Stratification in the upper water column is likely to increase the extent of the present ice-free areas of the Arctic, assuming no marked increase in wind strength.
- Present assessments indicate that UV-B radiation generally represents only a minor source of direct mortality (or decreased productivity) for populations, particularly in DOC-protected coastal zones. However, for those species whose early life stages occur near the

surface, it is possible that under some circumstances – a cloudless sky, thin ozone layer, lack of wind, calm seas, low nutrient loading – the contribution of UV-B radiation to the productivity and/or mortality of a population could be far more significant. Thus, it is likely that UV-B radiation can have negative impacts (direct and/or indirect effects) on marine organisms and populations. However, UV-B radiation is only one of many environmental factors responsible for the mortality typically observed in these organisms.

Many aspects of the interaction between the atmosphere and the ocean, and between climate and the marine ecosystem, require a better understanding before the high levels of uncertainty associated with the predicted responses to climate change can be reduced. This can only be achieved through monitoring and research, some areas requiring long-term effort. For some processes, the ocean responds more or less passively to atmospheric change, while for others, changes in the ocean themselves drive atmospheric change. The ocean clearly has a very important role in climate change and variability. Large, long-lived arctic species are generally conservative in their life-history strategies, so changes, even dramatic changes, in juvenile survival may not be detected for long periods. Zooplankton, on the other hand, can respond within a year, while microorganisms generally exhibit large and rapid (within days or weeks) variations in population size, which can make it difficult to detect long-term trends in abundance. Long data series are thus essential for monitoring climate-induced change in arctic populations.

Although the ACIA-designated models all project that global climate change will occur, they are highly variable in their projections. This illustrates the great uncertainty underlying attempts to predict the impact of climate change on ecosystems. The models do not agree in terms of changes projected to wind fields, upon which ocean circulation and mixing processes depend. Thus, conclusions drawn in this chapter regarding future changes to marine systems are to a large extent based on extrapolations from the response of the ocean to past changes in atmospheric circulation. This is also the case for predictions regarding the effects of climate change on marine ecosystems. The present assessment has been able to provide some qualitative answers to questions raised regarding climate change, but has rarely been able to account for non-linear effects or multi-species interactions. Consequentially, reliable quantitative information on the response of the marine ecosystem to climate change is lacking.

Some important gaps in our knowledge are listed below. These require urgent attention in order to make significant progress toward predicting and understanding the impacts of climate change on the marine environment.

- Thermohaline circulation (THC)
- Ocean currents and transport pathways
- Vertical stratification
- Location and intensity of ocean fronts
- Release of greenhouse gases and sequestration of carbon
- Species sensitivity to climate changeatch/mismatch between predators and prey
- Indirect and non-linear effects on biological processes
- Competition when/if new species are introduced into the ecosystem
- Long-term UV-B exposure studies

Principles of Conserving the Arctic's Biodiversity (ACIA Chapter 10)

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Introduction

Biodiversity is fundamental to the livelihoods of Arctic people. The species used range from mammals, fish and birds to berries and trees. However, each of these species also depends both upon a range of other species within the Arctic ecosystems and upon the ecological processes that occur in those ecosystems. The Convention on Biological Diversity defines 'biological diversity' (often shortened to 'biodiversity') as meaning "the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part; this includes diversity within species, between species and of ecosystems" This definition clearly implies that biodiversity, and both its conservation and utilisation, must be viewed at three levels - the gene, the species and the ecosystem (or habitat). A changing climate can affect all three of these levels of biodiversity, especially by changing the major ecosystem processes of photosynthesis and decomposition.

Conserving Biodiversity

There are many competing pressures on the ability of an individual, group, organisation or nation to conserve the biodiversity of the Arctic, of which six will be highlighted. First, no species which is native in the Arctic should be allowed to become extinct. Second, genetic variation within these species needs to be conserved because this ensures the greatest chance of the species' adaptation to a changing environment. Third, the ecosystems in which these species occur need to be conserved, because each species is an integral part of a food web (and hence with other species dependent upon it). Fourth, human populations are themselves an integral part of the Arctic's biodiversity and food webs. Fifth, non-native species and external human pressures will present challenges to the Arctic's genes, species and ecosystems, and hence risk assessments are a vital factor in managing such new pressures. Finally, protected areas are not a universal panacea for the conservation of the Arctic's biodiversity, but should be viewed as land and water managed for the primacy of nature in a broader geographical area where other land- and water-uses have primacy.

Predicted Influences of Climate Change

(1) *There will be changes in the geographical ranges of species and habitats.* In a warming environment it might generally be assumed that ranges will move northwards and locally they will move uphill. There will, however, be large differences in the distance moved, depending upon a species' ability to move. New combinations of species that have moved at different speeds might give rise to novel communities. In the sea, the retreat of sea ice northwards will result in the ice-edge species moving northwards. On land, there will be a squeeze, as for the spruce *Picea abies* that is constrained in its northward migration by the barrier of the Arctic Ocean.

(2) *There will be changes in the extent of many habitats.* We know that the response of each of the present-day Arctic habitats is likely to be individualistic, and that it will depend upon the dynamics of the populations and communities, as well as on a host of species interactions such as competition, predation, parasitism, hyperparasitism and mutualism. There is some evidence that changes might be relatively fast, especially in the marine environment. To understand what might occur in the Arctic in the future, the habitats occurring in the sub-Arctic and Boreal zones today offer the best guidance.

(3) *There will be changes in the abundance of Arctic species.* These changes will be complex, depending upon the rate of movement of the species, the amount of habitat available for them, and upon the species' own physiology and biochemistry. For example, experiments have shown that birch (*Betula pendula*) trees grown in elevated CO_2 atmospheres can produce more that half as much more biomass than trees grown in ambient CO_2 atmospheres, and that their roots are associated with a different set of species of mycorrhizal fungi. Sea surface temperatures are also known to have large effects upon the breeding success of seabirds, such as the common guillemot or muree (*Uria aalge*).

(4) *There will be changes in genetic diversity.* It has recently been said that landscape genetics promises to facilitate our understanding of how geographical and environmental features structure genetic variation at both the population and individual levels. Given the fact that there is relatively little knowledge about the genetical variation of most Arctic species, we have to make the assumption that geographical and environmental factors have structured the genetic variation that we have today. This has been verified for the common eider duck (*Somateria mollissima*), in which five major groups have been identified. Because many species in the Arctic are at the edge of their range, where gene flow may be more restricted than in the centre of a species' range, speciation may be occurring and hence the conservation of the gene pool is even more important.

(5) *There will be a change in the behaviour of migratory species.* To avoid the cold of the Arctic winter, species need to adopt a strategy of cold avoidance. Some migrate to warmer environments (e.g. from tundra to forest), whereas others exploit the food resources of the Arctic during the summer breeding season (e.g. many birds such as waders and geese). As the Arctic's biodiversity changes, there will be effects on migratory species. In some instances the breeding habitat might be further from the wintering habitat, necessitating expenditure of more energy. Often birds have 'stopping-off' points in boreal or temperate latitudes between the two ends of the migration route; these could also be affected. It is unknown how the migration routes might change, but such changes could be important for people dependent upon migratory species for their food.

(6) *Some non-native species are likely to become problematic.* To date the Arctic has escaped the major problems that invasive species have caused elsewhere on the planet. Terrestrial environments will be prone to invasions from the south, and there is already some evidence of the movement of insects that can defoliate large areas of sub-Arctic forests. Freshwater environments are susceptible to invasion by fish, often escaping from fish farming cages, and the parasites that are associated with them. Marine environments are prone to the introduction of species in ballast water; with the prospect of the Arctic Ocean being accessible to shipping for more of the year, the probability of accidental introductions of invasive species becomes greater. The risks to the Arctic's biodiversity could be huge and hence extreme precaution is needed when contemplating the introduction of non-native species to the Arctic.

(7) *Protected areas will need to be managed in different ways.* It has been suggested that there are three approaches to managing protected areas under the scenarios of climate change. There are currently about 400 protected areas with extents of greater than 10 km^2 in the Arctic, and

consideration will need to be given to their management. Static management involves the 'business-as-usual' scenario, conserving the current species and communities within the present boundaries, using the existing goals. Passive management would accept the ecological response to climate change, and allow evolutionary processes to take place unhindered. Adaptive management would maximise the capacity of species and communities to adapt to climate change through active management so as to slow the pace of change or to facilitate change to a new climate-adapted state. There could also be schemes of hybrid management whereby two or more of these approaches could be adopted on any one protected area.

Actions Required

What should be done now before the anticipated changes occur? First, it is important to document the current state of the Arctic's biodiversity. We know that the Arctic has about 1735 species of vascular plants, 600 bryophytes, 2000 lichens, 2500 fungi, 75 marine and terrestrial mammals, 240 birds, 3300 insects, 300 spiders, 5 earthworms, and so on. Local inventories of biodiversity have generally not been carried out, though the inventory for Svalbard is a striking exception, recording both native and non-native species in both terrestrial and marine environments. Such work requires trained ecologists, trained taxonomists, circum-Arctic knowledge, and a focus on all three levels (genes, species and ecosystems) of biodiversity.

Second, the changes that take place in the Arctic's biodiversity need to be identified. Ecological succession is a process whereby communities of plants and animals naturally change over time. Management of the Arctic's biodiversity, in the sea, in fresh water, or on land, must work with ecological succession and not against it. In many sciences, modeling has been developed so that predictions can be made. However, where biodiversity is concerned, models have not yet become particularly sophisticated so that there are few predictions. Considerably more effort needs to be invested in developing predictive models that can explore changes in biodiversity under the various scenarios of climate change.

Third, changes in the Arctic's biodiversity need to be recorded and the data shared. In a situation where so much uncertainty surrounds the conservation of biodiversity, knowledge of what has changed, where it has changed, and how quickly it has changed, becomes critically important. Monitoring biodiversity, especially on a circum-Arctic basis, must be a goal, and a circum-Arctic monitoring network needs to be fully implemented so as to determine how the state of biodiversity is changing, what the drivers of change are, and how other species and people respond. It is obvious that only a few aspects of the Arctic's biodiversity can actually be monitored, and hence it becomes important to devise a series of indicators that can be widely monitored. Such indicators should be made publicly available in formats that can inform public opinion, educators, model-builders, decision-makers and policy-makers.

Finally, new approaches to managing the Arctic's biodiversity need to be explored. Best practice guidelines should become available on a circumpolar basis. The Circumpolar Protected Area Network (CPAN) needs to be completed and reviewed so as to ensure that it does actually cover the full range of the Arctic's present biodiversity. An assessment needs to be made for each protected area of the likely effects of climate change, and in the light of this assessment the methods of management for the future and any revisions to the area's boundary determined. However, biodiversity is not confined to protected areas, and hence an ethos of biodiversity conservation needs to be incorporated into all aspects of policy development and all aspects of managing the Arctic's seas, land and fresh waters. This poses questions of resources and priorities, but it is essential that the Arctic's ecosystems continue to exist and function in a way that such services as photosynthesis, decomposition, and purification of pollutants, continue in a sustained manner.

Management and Conservation of Wildlife in a Changing Arctic (ACIA Chapter 11)

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Climate changes in the Arctic in the past have had major influences on the ebb and flow in availability of wildlife to indigenous peoples and thus have influenced the distribution of peoples in the Arctic and the development of their cultures. As northern cultures have developed, their relationships to wildlife also were influenced beyond strictly subsistence dependency through trade or other economic relationships, both internal to their own cultures and with other cultures. Trade in animal parts, especially skins and ivory of marine mammals; the semi-domestication of reindeer; and trapping and sale of fur-bearing animals go far back in time. Over the last two to three centuries cash income has sometimes become important from selling meat and hides and as well as through home industries producing saleable craft items from animal parts. Wildlife in the Arctic is valued by many who live outside of the Arctic for its attraction for viewing and photographing (especially whales, sea birds, polar bears, and caribou), for incorporation in art depicting the arctic environment, and for associated tourism. Sport and trophy hunting of wildlife bring many to the Arctic with associated economic benefits to local residents through services they provide. Others value the Arctic through virtual recognition of and fascination for the role of wildlife species in the dynamics of arctic ecosystems, many of whom may never visit the Arctic but learn about arctic wildlife through the printed and visual media. Responsibility for management and conservation of wildlife in the Arctic clearly falls heavily on the residents of the Arctic, but also on the global community that shares in the use of arctic resources and the appreciation for wildlife and other values of the arctic environment. A sense of global stewardship toward the Arctic is critical for the future of Arctic wildlife and its peoples.

Throughout most of the Arctic, natural ecosystems are still functionally intact (Chapters 6-8) and threats to wildlife typical for elsewhere in the world – extensive habitat loss through agriculture, industry, and urbanization – are absent or are localized. Similarly, introduced and invading alien species are scarce. However, change in the Arctic is accelerating. Contaminants from the industrialized world to the south have reached arctic food chains, threatening the health and reproduction of some marine mammals and birds and the humans who include them in their diets. Energy and mineral extraction developments in the Arctic, although localized and widely scattered, nevertheless contribute to the pollution and contamination of the waters, atmosphere, and lands of the Arctic and result in local loss of wildlife through habitat destruction, excessive hunting, and other cumulative impacts. Protection of critical wildlife habitats in the Arctic is becoming increasingly recognized as essential for both the conservation of arctic wildlife and its sustainable harvest by residents of the Arctic as pressures from outside of the Arctic for exploitation of its resources increase.

Management of wildlife and its conservation, as practiced in most of the Arctic, is conceptually different than at lower latitudes where management efforts often focus on manipulation of habitats to benefit wildlife. Residents of the Arctic have in the past often seen little apparent justification for conventional wildlife management and have resisted additional systems for wildlife management and conservation imposed from outside of the Arctic, particularly when these systems rely heavily on new and strange technologies and are based on unfamiliar tenets.

Increased emphasis by those living outside of the Arctic on conservation of the flora and fauna of the Arctic has focused on maintaining the Arctic's biodiversity, valuing all its ecosystem components and relationships. This has understandably appeared hypocritical to many arctic indigenous peoples dependent on sustainable harvest of arctic wildlife and in view of their past resistance to over exploitation of marine mammals and birds for oil and skins to serve interests outside of the Arctic. Thus, some indigenous peoples have questioned the justification for wildlife management in the Arctic as a discrete aspect of ecosystem or land use management. In other areas, systems of co-management have developed, giving local residents a greater role in the practice of wildlife management if not in determining the premises on which it is based.

Throughout much of the Arctic, harvesting of wildlife for food and furs through hunting and trapping has, nevertheless, been the most conspicuous influence that residents of the Arctic have had on arctic wildlife in recent decades. It was the overexploitation of wildlife during the period of arctic exploration and whaling in the 18^{th} and 19^{th} centuries that led to the extinction of the Steller's sea cow in the Bering Sea and the great auk in the North Atlantic, and drastic stock reductions and local extirpation of several other terrestrial and marine mammals and birds. In many regions of the Eurasian Arctic, the adoption of reindeer herding by indigenous hunting cultures led to the extirpation or marked reduction of wild reindeer (caribou) and drastic reductions of wolves, lynx, wolverines, and other potential predators of reindeer. In recent decades heavy grazing pressure by semi-domestic reindeer has altered plant communities in parts of the Fennoscandian and Russian Arctic. This has in some areas been exacerbated by encroachment of timber harvest, agriculture, hydroelectric development, and oil and gas exploration within traditional grazing areas. Large-scale extraction of nonrenewable resources has accelerated in the Arctic during the latter half of the past century with impacts on some wildlife species and their habitats, especially in Alaska from oil production, in Canada from mining for diamonds and other minerals, and in Russia primarily from extraction of nickel, apatite, phosphates, oil, and natural gas.

Among the factors that influence arctic wildlife, harvest of wildlife through hunting and trapping is potentially the most manageable, at least at the local level. Indigenous peoples throughout much of the North are asserting their views and rights in wildlife management, in part through increased political autonomy over their homelands. However, people still feel largely powerless to control influences on wildlife and wildlife habitats brought about through climate change, or large-scale resource extraction in both the marine and terrestrial environments, changes largely resulting from the effects of humans living outside of the Arctic.

Along with the increasing political autonomy of indigenous peoples of the Arctic in recent decades, these arctic residents are starting to influence when, where, and how industrial activity may take place in the Arctic. Part of this process has been the consolidation of the efforts of indigenous peoples across national boundaries to achieve a greater voice in management of wildlife and other resources through international groups such as the Inuit Circumpolar Conference (ICC) and the Indigenous Peoples Secretariat (IPS) of the Arctic Council. The stage appears to be set for indigenous peoples of the Arctic to become major participants in the management and conservation of arctic wildlife. The legal institutions, however, encompassing treaty and land rights and other governmental agreements vary regionally and nationally throughout the Arctic posing differing opportunities and constraints on how structures for wildlife management and conservation can be developed.

Conservation of wildlife in the Arctic requires sound management and protection of wildlife habitats at the local, regional, and national levels if the productivity of those wildlife populations that arctic peoples are dependent upon is to be sustained. Wildlife populations and their movements in both the marine and terrestrial environments transcend local, regional, and national boundaries, thus successful management and conservation of arctic wildlife must also transcend political boundaries through international agreements and treaties. Many of the pressures on arctic wildlife originate outside of the Arctic, such as contaminants in marine wildlife, habitat alteration through petroleum and mining developments, and climate changes resulting from increases in greenhouse gases. It seems clear that responsibility for maintaining the biodiversity that characterizes the Arctic, the quality of its natural environment, and the productivity of its wildlife populations must be exercised through global stewardship.

Effective wildlife management and associated conservation in a changing Arctic requires:

- Inclusion of arctic residents in the monitoring, inventory, and regulation of harvest and conservation of wildlife.
- Inventory of wildlife populations and their habitats for assessing changes in distribution, movements, and population trajectories that may be the consequence of climate change or other human-induced changes in the natural environment.
- Restructuring of wildlife management systems in the Russian North that remain unchanged since the Soviet era.
- Development of regional land and water use plans that enable layout of proposed human activities on the land, such as roads, communities, other structures, and their cumulative effects to avoid conflicts with critical habitats of wildlife, their movement corridors, and patterns of human use of the wildlife.
- Areas designated to protect critical wildlife habitat units may at times need to be altered through expansion, relocation, or removal of protection in response to major changes in wildlife distribution and habitat use brought about through climate-induced or other changes in the land and marine environments.
- The international or bi-national nature of many species of marine wildlife requires international efforts in the development of marine area use and agreements to assure protection of critical habitats for marine wildlife.
- Understanding that marine ecosystems are more difficult to study and less well known than terrestrial ecosystems and require more complex and costly research efforts if arctic wildlife in the marine environment is to be effectively conserved and managed.

Hunting, Herding, Fishing and Gathering: Indigenous Peoples and Renewable Resource Use in the Arctic (ACIA Chapter 12)

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This paper summarises some of the key findings of Chapter 12 of the Arctic Climate Impact Assessment, which deals with terrestrial and marine resource use by indigenous peoples. Indigenous peoples throughout the Arctic maintain a strong connection to the environment through hunting, herding, fishing and gathering renewable resources. These practices provide the basis for food production and have endured over thousands of years, with cultural adaptations and the ability to utilize resources often associated with or affected by seasonal variation and changing ecological conditions.

Climatic variability and weather events often greatly affect the abundance and availability of animals and thus the abilities and opportunities to harvest and process animals for food, clothing and other uses. Many species are only available seasonally and in localized areas and indigenous cultures have developed the capacity and flexibility to harvest a diversity of animal and plant species. They have, in many cases, also shown resilience in the face of severe social, cultural and economic change, particularly in the last one hundred years.

The longstanding dependence of contemporary indigenous societies on hunting, herding, fishing and gathering continues for several critically important reasons. One main reason is the economic and dietary importance of being able to access customary, local foods. Many of these local foods – fish, and meat from sea mammals or caribou and birds, for instance, as well as berries and edible plants – are nutritionally superior to the foodstuffs which are presently imported (and which are often expensive to buy). Another reason is the cultural and social importance of hunting, herding and gathering animals, fish and plants, as well as processing, distributing, consuming and celebrating them.

These activities remain important for maintaining social relationships and cultural identity in indigenous societies. They define a sense of family and community and reinforce and celebrate the relationships between indigenous peoples and the animals and environment upon which they depend. Hunting, herding, fishing and gathering activities are based on continuing social relationships between people, animals and the environment. As such, they link people inextricably to their histories, their contemporary cultural settings, and provide a way forward for thinking about sustainable livelihoods in the future.

Arctic communities have experienced, and are experiencing, stress from a number of different forces that threaten to restrict harvesting activities and sever these relationships. The Arctic regions are tightly tied politically, economically and socially to the national mainstream and are inextricably linked to the global economy. Rapid social, economic and demographic change, resource development, trade barriers and animal-rights campaigns have all had their impacts on hunting, herding, fishing and gathering activities.

For many Arctic residents, consuming food from animals is fundamentally important for personal and cultural well-being. Indigenous peoples have reported their loss of vitality, decline in health and personal well-being when they are unable to eat traditional/country foods. These problems do not only emerge when climate change denies people access to traditional/country foods, but are very much linked to problems associated with the undermining of local modes of production. The erosion of a person's position as a provider of welfare to family and community also has serious ramifications.

The conservation of Arctic wildlife and ecosystems depends in part on maintaining the strength of the relationship between indigenous peoples, animals and the environment, and securing the rights of indigenous peoples to continue customary harvesting activities. As the ACIA shows, these activities and relationships appear to be threatened by severe climate change. The potential impacts of climate change on harvesting wildlife resources are of fundamental concern for the social and economic well-being, the health and cultural survival of indigenous peoples throughout the Arctic, who live within institutional, legal, economic and political situations that are often quite different from non-indigenous residents. Furthermore, indigenous peoples rely on different forms of social organisation for their livelihoods and well-being. Many of these concerns about climate change arise from what indigenous peoples are already experiencing in some areas, where climate change is an immediate and pressing problem, rather than something that may happen, or may or may not have an impact in the future.

The aims of Chapter 12 are:

- to discuss the contemporary economic, social and cultural importance of harvesting renewable resources for indigenous peoples;
- to provide an assessment of how climate change has affected, and is affecting, harvesting activities in the past and in the present;
- through a selection of detailed case studies based on extensive research with indigenous communities in several Arctic settings, to discuss some of the past, present and potential impacts of climate change on specific activities and livelihoods.

The case studies in Chapter 12 (from Alaska, Yukon, Northwest Territories, Nunavut, and the Russian North) have been selected to provide a sense of what impacts climate change is having in the present, or could have in the near future on the livelihoods of indigenous people, and is illustrative of the common challenges faced by indigenous peoples in a changing Arctic.

Part of the purpose of Chapter 12, although not its primary aim, is also to assess what adaptations have enabled communities to succeed in the past and what extent these options remain open to them. There is little data published on this area, but based on what is available the chapter shows that while indigenous peoples have often generally adapted well to past climate change, the scale and nature of current and predicted climate change brings an altogether different sense of uncertainty for indigenous peoples, presenting different kinds of risks and threats to their livelihoods.

Chapter 12 illustrates the complexity of problems faced by indigenous peoples today and underscores the reality that climate change is but one of several, often intersecting problems affecting their livelihoods. The chapter emphasises the urgency for further extensive, regionally-focused research on the impacts of climate change on hunting, herding, fishing and gathering activities, research that will not only contribute to a greater understanding of climate impacts, but will place these impacts within a broader context of rapid, social and economic change.

Fisheries (ACIA Chapter 13)

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Introduction

This chapter deals largely with the effects of climate change on commercial fisheries and the impacts of these on society as a whole (see Chapters 9, 10 and 11 on implications for indigenous peoples). Arctic fisheries of selected species are described in the following regions: the Northeast Atlantic consisting of the Barents and the Norwegian Seas; the waters around Iceland and Greenland; the waters off northeastern Canada; and the Bering Sea. The species discussed are: first, those few species, which are circumpolar (capelin, Greenland halibut, northern shrimp and polar cod); and, second, those additional species, which are of commercial importance in specific regions. These species include stocks of Atlantic cod, haddock, Alaska pollock, Pacific cod, snow crab and a number of others. Because marine mammals play an important role in northern marine ecosystems and can be commercially important, they are also considered in this chapter.

Methods

In order to identify the possible effects of climate change on fish stocks and the fisheries based on them in the Arctic, selected case studies from the 20th Century involving both the effects of cooling and warming of the marine environment have been used. However, there are several possible caveats that one must be aware of when attempting to interpret such case studies. The most important of these are:

1) Commercial fisheries in Arctic regions are based on a number of species belonging to ecosystem complexes. The dynamics of these ecosystems are not well understood in many cases. This imparts a significant degree of uncertainty to evaluating future response of individual species and stocks to climate change.
2) It has historically proven difficult in many cases to identify the relative importance of fishing and the environment on changes in fish populations and biology and current fish populations are different in abundance and biology from those in the past due to anthropogenic effects (exploitation rates).

As a result it is uncertain whether current fish populations will respond to climate changes as they may have in the past.

Once the fish population changes have been evaluated, an attempt was made to relate those changes to economic and other changes in society. That introduces a third set of methodological challenges, as social change is driven by a number of factors, of which environmental change is but one.

Conclusions

On balance it appears likely that a moderate warming (up to 3˚C) will improve conditions for some of the most important commercial fish stocks, as well as for aquaculture, in Arctic regions (see Chapter 8). This will likely take place through more primary production due to less ice coverage and more extensive habitat areas for sub-Arctic species like cod and herring. There is also some chance that global warming will induce an ecosystem regime shift in some areas with a different species composition. Changing environmental conditions are also likely to be deleterious for some species and beneficial for others. Therefore, relative population sizes, rates of fish growth and geographical distribution of fish stocks are likely to be altered. Adjustments will then have to be made in the Arctic commercial fisheries. Unless there is a dramatic climatic change over a very short time period, these adjustments are likely to be relatively minor and will probably not entail major economic and social costs.

In this chapter the possible effect of global warming on four major ecosystems, i.e, the Northeast Atlantic (Barents and Norwegian Seas), the central North Atlantic (Iceland/Greenland), Northeast Canada (Newfoundand/Labrador) and the North Pacific (Bering Sea) is considered. There are substantial differences between these regions in that the Barents and Norwegian Seas and Icelandic waters are of a sub-Arctic/temperate type, while Arctic influence is much greater in Greenland waters, off NE-Canada and in the Bering Sea. It follows, therefore, that climate warming need not affect all of these areas in the same or similar manner. Furthermore, the length of useful time series on historical environmental variability and associated changes of hydrobiological conditions, fish abundance and migrations vary greatly from one region to another. And, finally, there are differences in species interactions and variable fishing pressure, which have to be considered.

Due to heavy fishing and stock depletions, the Barents Sea, Icelandic waters and probably also the Bering Sea could, through more efficient management, yield larger catches of many fish stocks. For that to happen research must be increased, and cautious management strategies must continue to be implemented and complied with. A moderate warming could enhance the processes of rebuilding stocks and, furthermore, generally result in higher sustainable yields of most stocks, i.e. through enlarged distribution areas and increased availability of food in general. On the other hand, warming could also cause fish stocks to change their migratory ranges and area of distribution. As history has demonstrated, this could trigger conflict among nations over distribution of fishing opportunities and require tough negotiations to arrive at viable solutions as regards international regimes fisheries management.

Greenland and NE-Canadian waters are very different cases. These are much more Arctic in nature and e.g. Greenlandic waters appear not to be able to support more temperate species like cod and herring except during warm periods. For Greenland, there are examples from the 20th Century that demonstrate this point. No cod in the first two and a half decades, a large local self-sustaining cod stock from about 1930 and until the late 1960s, apparently initiated by larval and 0-group drift from Iceland. With a climatic status quo nothing much can be expected to change at Greenland. On the other hand, a 'moderate warming' like that of the 1920s, resulting in warm conditions which lasted until the late 1960s, could bring about some dramatic changes in species composition, a scenario where cod would play the most important role by far and double the value of exported goods. The NE-Canadian case is an extreme example of a situation where a stock of Atlantic cod, (the so-called northern cod), which had sustained a large fishery for at least two centuries, is suddenly gone. Opinion differs with regard to how this could have happened, where some believe that inhospitable environment is the main cause while others hold the view that the stock appears to have simply been fished out. In this case it is worth noting that the Newfoundland-Labrador ecosystem is open, i.e. there are no temperature barriers, to the south and west. In earlier times of climatic adversities the northern cod could therefore have backed out and then repopulated its earlier distribution areas when conditions improved again. In the present situation, however, the northern cod is so depleted that, due to its slow growth rate, it will very likely take decades to rebuild – even under the conditions of a warming climate.

The economic and social impacts of altered environmental conditions and their effects on fish stocks depend crucially on the ability of the relevant social structures, not the least the fisheries management system, to generate the necessary adaptations to the changes. It is unlikely that the impact of global warming in the 21st Century, as signaled by the 'moderate' scenarios used here, will have long-term economic or social impacts on a national scale. A possible exception is the large boost to the national economy of Greenland should a large local cod stock and fishery, like that of the mid 20th Century, recur.

Certain regions in the Arctic, i.e. those heavily dependent on fisheries or marine mammals and birds in direct competition with a fishery may, however, be radically affected. Local communities in the north are however exposed to a number of forces of change. Economic marginalization, depopulation, globalization-related factors and public policies in the different countries, are most likely going to have a stronger impact on the future development of northern communities than a moderate climate change, at least in the foreseeable future.

An evaluation of what could happen should climate warming proceed beyond what here is defined as moderate (plus 1°-3°C), is not attempted. This is beyond the existing range of available data and would therefore be of limited value. In general terms, however, it is likely that at least some of the ecosystems would experience reductions in the present-day commercial stocks which, on the other hand, might be replaced partially or in full by species from warmer waters.

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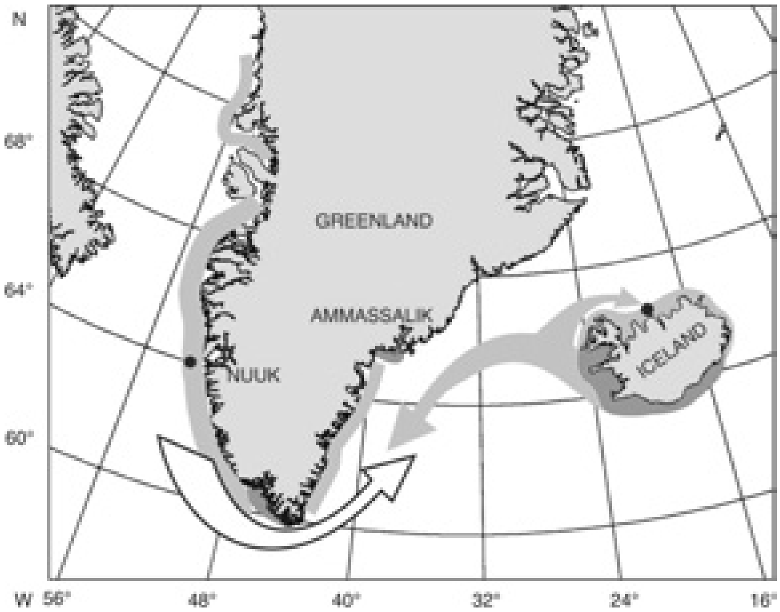

Figure 1. The arrows show the drift of cod larvae and 0-group to Greenland and return spawning migrations during the warm period 1920-1965). The light grey shaded area at Greenland shows the maximum extent of cod distribution during the latter half of the warm period 1920-1965. Before 1920 only a few cod had been found near Cape Farewell and Ammassalik (dark grey shade). Adapted from Vilhjalmsson 1997

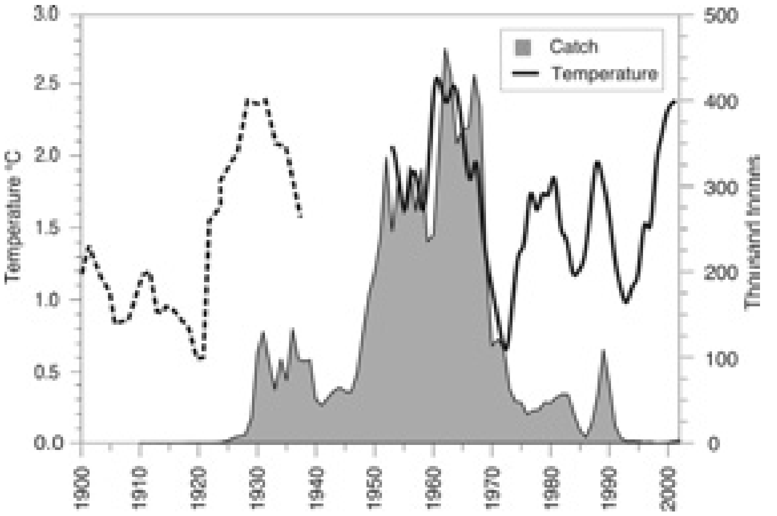

Figure 2. Temperature variations west of Nuuk (black dot in Fig. 1) and the cod catch from W-Greenland waters 1900-2002. Overfishing greatly accelerated the rapid decline of this stock in the late 1960s and the early 1970s. Adapted from Buch et al. 1994 with later data added.

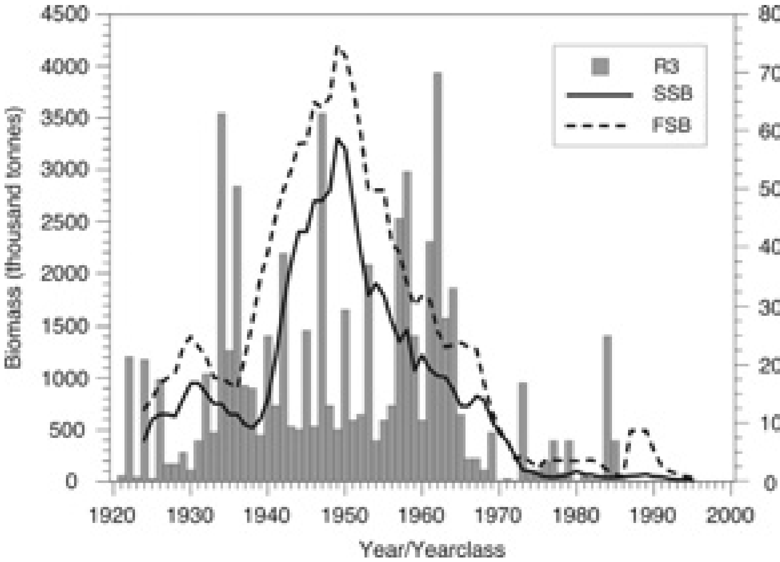

Figure 3. Fishable and spawning stock biomass and recruitment to the W-Greenland cod stock 1920-2000. This cod stock produced very large year classes from the mid-1930s until the mid-1960s. After that, almost all recruitment to the W-Greenland cod is the result of larval drift from Iceland in 1973 and 1984. Adapted from Buch et al. 1994 with later data added.

Boreal Forest and Agricultural Responses to Climate Warming (ACIA Chapter 14)

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Introduction

The boreal region covers about 17% of the earth's land surface area. The boreal forest affects Earth's climate through carbon uptake and release and albedo. Boreal forests influence global levels of atmospheric carbon dioxide and other greenhouse gasses by taking up CO2 in growth, and storing carbon in live and dead plant matter and releasing carbon through decomposition of dead organic matter, live plant and animal respiration, and combustion during fire. Humans influence carbon uptake and storage by rearrangement of forest age classes, timber harvest, suppression of wildfires, selection of tree species, fertilisation, and thinning regimes. Residents of the boreal region depend on the products and resources of the forest for traditional ways of life that have become impractical to follow elsewhere on earth. Agriculture has existed in the ACIA region for well over a millennium, and today consists of a mixture of commercial agriculture on several thousand farms and widespread subsistence agriculture.

Methods

The ACIA analysis included a review and synthesis of primary scientific and resource management literature. Primary data sets included the record of key climate variables at 14 sites broadly distributed across the boreal region and chosen to represent major population, trade, or transportation centers. The analysis examined output of 5 GCM model scenarios for the grid cells containing the 14 sites for mean monthly temperature, total monthly precipitation, and Growing Degree Days (GDD). Tree-ring data sets from northern trees provide a direct record of the relationship between past climate and above-ground forest growth and projections of future growth.

Conclusions

In the period between 9000 and 7000 B.P. trees occurred in at least small groups in what is now treeless tundra nearly all the way to the Arctic coastline across the Russian north. Mean July temperature along the Russia Arctic coastline was 2.5 to 7.0^{0}C higher than currently. Past forest advance during suggests similar treeline change is likely in scenarios that produce similar levels of warming, and that ecosystems present today have the capacity to respond and adjust to such climate fluctuations. At 6000 BP (the Postglacial thermal maximum) northern treeline on the Taymir Peninsula, which is currently the farthest north in the world, was at least 150 km further north than at present. In northeast Canada the black spruce forest limit of Quebec has remained stable during the last 2000-3000 yr BP, but in recent decades milder winters have permitted low stems to emerge into the upright form. In the Polar Ural Mountains, larch reproduction is associated with warm weather, and newly established trees have measurably expanded forest cover during the 20th century, although there is a time lag between warming and upslope treeline movement. At about 6000 BP, ring growth of larch trees on the Taymir Peninsula of Russia surpassed the average of the last two millennia by 1.5 to 1.6 times. Tree growth and warm season temperature irregularly decreased in northernmost Eurasia and North America from the Postglacial thermal maximum through the end of the 20th century. Long-term tree-ring chronologies record a Medieval Warm Period about one thousand years ago, a colder Little Ice Age ending about 150 years ago, and various types of climate change involving warming more recently. Recent decades are the warmest in at least a millennium. Temperature and tree growth records generally change at the same time and in the same direction across much of the Arctic and Subarctic, although opposite temperature and tree growth trends occur in specific subregions.

All the scenarios produce warming within the boreal region greater than reconstructions of climate for nearly the last 1000 years. Climate warming in the last several decades is already associated with both improved and decreased current (not projected) boreal tree growth, depending on species, site type, and region. Some tree growth declines are large in magnitude and have been detected at different points across a wide area (although the total extent of declines has not been delineated) as the result of temperature-induced drought stress. Other tree growth declines are not currently explained. Reduced growth by high temperatures is common in treeline white spruce of western North America, suggesting less potential for treeline movement under a warming climate than previously believed. Boreal forest tree growth is increasing in some locations, generally where moisture and nutrients are not limiting such as boreal regions of Europe and eastern North America. The 5 GCM scenarios produce climates that apparently would not allow the growth of commercially valuable white spruce types and widespread black spruce types in Alaska and probably western boreal Canada, based on empirically calibrated measurements. The upper range of scenario conditions represent climates that may have crossed ecological thresholds, and it is possible that novel ecosystems could result as happened during major periods of global climate change in the past. If additional moisture were available, trees on many of the driest sites would not be as stressed as current temperature relationships indicate.

Large-scale forest fires and outbreaks of tree-killing insects are naturally characteristic of the boreal forest, are triggered by warm weather, and promote many important ecological processes. Boreal forests are a major storehouse of carbon in trees and soils, containing approximately 20% of the world's reactive soil carbon, an amount similar to that held in the atmosphere. On a global basis, atmospheric carbon equal to 15-30% of annual emissions from fossil fuels and industrial activities is taken up annually and stored in the terrestrial carbon sink. During the years 1981-1999, it is estimated that the three major factors affecting the terrestrial carbon sink were biomass carbon gains in the Eurasian boreal region and North American temperate forests, and losses in areas of the western North American boreal forest. Recent patterns of boreal forest disturbance are consistent with a climate warming influence expressed as 1) a greater frequency of fire or insect outbreaks, 2) more extensive areas of tree mortality, and 3) more intense disturbance resulting in higher average levels of tree death or severity of burning.

Carbon uptake and release at the stand level in boreal forests is strongly influenced by the interaction of nitrogen, water, and temperature influences, acting together, on forest litter quality and decomposition. Warmer forest soil temperatures that occur following the death of a forest canopy by disturbance increase the rate of organic litter breakdown, and thus the release of elements for new plant growth (carbon uptake). The most likely mechanism for significant short-term change in boreal carbon cycling as a result of climate change is the control of species composition caused by disturbance regimes. Successional outcomes from disturbance have different effects on carbon cycling especially because of the higher level and availability of nutrient elements (and thus decomposition) in organic litter from broadleaf trees compared to conifers. Net global land use/land cover change, especially aggregate increases or decreases in the area of forest land, may be the most important factor influencing the terrestrial sink of carbon.

Different crops species, and even varieties of the same species can exhibit substantial variability in UV-B sensitivity. In susceptible plants, UV-B causes gross disruption of photosynthesis, and may also inhibit plant cell division. Damage by UV-B is likely to accumulate over the years in trees. Evergreens receive a uniquely high UV dose in the late winter, early spring, and at the beginning of the short growing season because they retain vulnerable leaf structures during this period of maximum seasonal UV-B exposure which is amplified by reflectance from snow cover. UV-B radiation plays an important role in the formation of secondary chemicals in birch trees at higher latitudes. Secondary plant chemicals released by willows exposed to UV-B might stimulate the herbivore resistance of birch. A lower level of animal browsing on birches because of this chemical change induced by UV-B could possibly improve the performance of birch over its woody plant competitors.

The five GCM scenarios all produce rising temperatures that would very likely enable crop production to advance northward throughout the century, with some crops now suitable only for the warmer parts of the boreal region becoming suitable as far north as the Arctic Circle. Average annual yield of farms would likely increase at the lower levels of warming due to climate suitability for higher yielding crop varieties and lower probabilities of low temperatures limiting growth. However, in warmest areas, increased heat units during the growing season may cause a slight decrease in yields since warmer temperatures can speed crop development and thereby reduce the amount of time organic matter (dry measure) is accumulated. Under scenario conditions, water deficits are very likely to increase or appear in most of the boreal region, the main exceptions being portions of eastern Canada, Iceland, and western Scandinavia, which experience the strongest maritime influence on their climates. In the later scenario period, unless irrigation is practiced, water stress would very likely negatively impact crop yields. Water limitation may become more important than temperature limitations for many crops in much of the region. Overall negative effects would not likely be stronger than positive effects on agriculture. Lack of infrastructure is likely to remain a major limiting factor for commercial agricultural development in the boreal region in the near future, and climate warming that thawed permafrost would affect land transportation routes. Shipping across the Arctic Ocean could fundamentally change the costs of shipping cargoes that affect agriculture. If climate warming is associated with migration of people northward, the larger resident population base is likely to stimulate the agricultural sector, ultimately expanding and improving infrastructure which would improve economic potential of agriculture. Even under scenario levels of climate warming, government policies regarding agriculture and trade will still have a very large, and perhaps decisive, influence on the occurrence and rate of agricultural development in the north.

Climate Change and Health in the Circumpolar North: Findings from the Arctic Climate Impact Assessment (ACIA Chapter 15)

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The nature of predicted climate related changes and variability, and characteristics of Arctic populations means that impacts of climate change on the health of Arctic residents will vary considerably depending on such factors as age, gender, socioeconomic status, lifestyle, culture, geographic location, and capacity of local health infrastructure and systems to adapt. It is more likely that populations living in close relationship with the land, in remote communities and those that already face a variety of health related challenges will be most vulnerable to climate changes in the future. Health status in many Arctic regions has changed significantly in the past decades related to a variety of factors and climate, weather and environment has had, and will likely continue to have a significant role in health in these regions in the future.

In the assessment of health impacts of climate change in the North conducted for the Arctic Climate Impact Assessment a number of *direct* and *indirect* impact mechanisms were identified and described. In this sense "direct impacts" refers to *those health consequences resulting from direct interactions with aspects of the environment that have changed or are changing with local climate* (i.e. resulting from direct interactions with physical characteristics of the environment: air, water, ice, land; e.g. exposure to thermal extremes). "Indirect impacts" refer to those health consequences resulting from indirect interactions mediated via human behaviors and components of the environment that have changed or are changing with local climate.

Direct health impacts may result via changes in the incidence of extreme events (avalanches, storms, floods, rockslides) which have the potential to increase the numbers of deaths and injuries each year. Direct impacts of winter warming in some regions may include a reduction in cold-induced injuries such as frostbite and hypothermia and a reduction in cold stress. As death rates are higher in winter than summer months, milder winters in some regions could reduce the number of deaths. Direct negative impacts of warming could include increased heat stress in summer months and accidents associated with unpredictable ice and weather conditions.

Indirect impacts from climate change in circumpolar communities may include increased mental and social stress related to changes in the environment and lifestyle and potential changes in bacterial and viral proliferation, vector borne disease outbreaks, as well as changes in the access to quality drinking water sources. Additionally, some regions may experience a change in the rates of illnesses resulting from impacts to sanitation infrastructure from melting permafrost and increased storm surges. Impacts to individuals' food security through changes in animal distribution and accessibility has the potential to have significant impacts on health as shifts from a more traditional diet to a more "western" diet are know to be associated with increase risks of cancers, diabetes, and cardiovascular disease.

Increased exposure to UV among Arctic residents has the potential to impact immune system's response to disease, influence skin cancer development and non-Hodgkins lymphoma as well as the development of cataracts. However, as the current rates of many of these ailments are low in small Arctic communities it is difficult to detect, let alone, predict any trends in their incidence in the future. Currently, the presence of environmental contaminants threaten the safety of traditional food systems, which in many cases are the central fabric of communities. Potential influence of shifts in temperature can affect transport to, distribution within and the chemical behaviour of environmental contaminants and therefore human exposure to these substances in northern regions.

It is critical to understand that these potential, and in some cases, currently observed changes are taking place in a context of social, economic, and physical change and evolution throughout the North. They therefore represent yet another source of stress on societies and cultures as they impact the relationship between people and their environment which is a defining element of many northern cultures. Through potential increases in factors influencing acculturative stress and mental health, climate related changes may further stress communities and individual psychosocial health.

Communities must be prepared to understand, document, and monitor changes in their area in order to adapt to shifts in their local environment now and in the future. The basis of this understanding is the ability to collect, organize and understand information indicative of the changes taking place and their potential impacts. To this end, a series of community indicators are proposed in the ACIA Health Chapter to support this development of capacity within northern regions and communities.

Climate Change and Arctic Infrastructure (ACIA Chapter 16)

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Introduction

This chapter discusses the potential impacts of climate change on Arctic infrastructure. Infrastructure is defined as facilities with permanent foundations or the essential elements of a community. It includes schools; hospitals; various types of buildings and structures; and facilities such as roads, railways, airports, harbors, power stations, and power, water, and sewage lines. Infrastructure forms the basis for regional and national economic growth.

Particular concerns are associated with permafrost warming and degradation, coastal erosion, the stability and maintenance of transportation routes, and industrial development.

Climate change is likely to have significant impacts on existing Arctic infrastructure and on all future development in the region. In most cases, engineering solutions are available to address climate change impacts, making the issue more of an economic than a technological one. It is possible that the uncertainty associated with projections of future climate change will increase the cost of new projects in the Arctic.

There are increased concerns related to the impact of projected climate change on Arctic infrastructure, particularly how future climate change may:

- increase the environmental stresses structures are exposed to, particularly in comparison to design specifications, and cause increased risk and damage to infrastructure and threat to human lives;
- affect natural hazards and the impacts of extreme events; and
- affect development scenarios for exploitation of natural resources in the Arctic.

Various aspects of changing climate on Arctic infrastructure are discussed in this presentation. Adaptation, mitigation and monitoring techniques that are necessary to minimize the potentially serious detrimental impacts are discussed.

Permafrost

Projected climate change is possible to be a factor in engineering projects if its effects go beyond those anticipated in the existing conservative approach. Therefore, engineering design should take into account projected climate change where appropriate and where the potential effects represent an important component of the geothermal design.

Permafrost engineers must address the problem of preserving infrastructure under projected future climate conditions. One solution is to construct new buildings as existing ones are damaged and abandoned. It is possible that this method will be inadequate, since the required rate of new structures rises exponentially using the climate projections presented in this assessment. In areas of warm, discontinuous permafrost, it is very difficult to find economic solutions to address the impacts of climate change on foundations or structures. These areas, together with the coastal zone, present the greatest challenges in a changing climate.

The sensitivity of permafrost soil strength to projected climate change can be mapped using a simple strength sensitivity index, such as the one proposed in this section. A risk-based procedure for analyzing structures based on their sensitivity to the potential consequences of climate change is a reasonable approach to incorporating climate change concerns into the design process.

Coastal Zone

The Arctic has approximately 200000 km of coastline, most of which is uninhabited. However, coastal development is critical to the economy and social well-being of nearly all Arctic residents.

Arctic coastal dynamics are often affected directly or indirectly by the presence of permafrost. Permafrost coasts are especially vulnerable to erosive processes as ice beneath the seabed and shoreline melts from contact with warmer air and water. Thaw subsidence at the shore allows additional wave energy to reach unconsolidated erodible materials. Low-lying, ice-rich Arctic permafrost coasts are the most vulnerable to thaw subsidence and subsequent wave-induced erosion.

Coastal communities are sensitive to climate change. Engineering solutions are available for shore protection (flood barriers, dikes, breakwaters, erosion control) but may not be able to reduce erosion rates sufficiently to save specific settlements. Moreover, while these protective measures may address one problem, they may create another by altering the dynamics of erosion and deposition processes. The combined problems of increased wave action, sea level rise, and thermal erosion have no simple engineering solutions, face the greatest challenge from a warming climate.

Thinner, less extensive sea ice is very likely to improve navigation conditions along most northern shipping routes, such as Canada's Northwest Passage and Russia's Northern Sea Route. However, decreasing sea-ice extent and thickness is very likely to affect traditional winter travel and hunting where sea ice has been used for these purposes.

With increased marine access to Arctic coastal seas, national and regional governments are likely to be called upon for increased services such as icebreaking assistance, improved sea-ice charts and forecasting, enhanced emergency response capabilities for sea-ice conditions, and greatly improved oil-ice cleanup capabilities. The sea ice, although thinning and decreasing in extent, will possibly become more mobile and dynamic in many coastal regions where land-fast ice was previously the norm. Competing marine users in newly open or partially ice-covered areas in the Arctic are likely to require increased enforcement presence and regulatory oversight.

Based on the scenarios presented in this chapter, a longer navigation season along the Arctic coast is very likely and trans-Arctic (polar) shipping is possible within the next 100 years.

Natural Hazards

Projected increases in temperature, precipitation, and storm magnitude and frequency are very likely to increase the frequency of avalanches and landslides. In some areas, the probability of severe impacts on settlements, roads, and railways from these events is very likely to increase.

Structures located on sites prone to slope failure are very likely to be more exposed to slide activity as groundwater amounts and pore water pressures increase.

An increasing probability of slides coupled with increasing traffic and population concentrations is very likely to require expensive mitigation measures to maintain a defined risk level. The best way to address these problems is to incorporate the potential for increasing risk in the planning process for new settlements and communication lines.

Engineering Design and Climate Change

In continuous permafrost, projected climate change is not likely to pose an immediate threat to the infrastructure. This assumption is only valid if the correct permafrost engineering design procedures have been followed; the infrastructure has not already been subjected to one of the factors mentioned at the beginning of this section or strains exceeding design values; and the infrastructure is not located on ice-rich terrain or along coastlines susceptible to erosion. Maintenance costs are likely to increase compared to the present, but it is possible to gradually adjust Arctic infrastructure to a warmer climate.

Projected climate change is very likely to have a serious effect on existing infrastructure located in areas of discontinuous permafrost. Permafrost in these areas is already at temperatures close to thawing, and further temperature increases are very likely to have extremely serious impacts on infrastructure. However, considerable engineering experience with discontinuous permafrost has been accumulated over the past century. Human interaction (such as pollution issues, fires, removing vegetation) and engineering construction very often lead to extensive thawing of both continuous and discontinuous permafrost. Techniques to address warming and thawing are already commonly used in North America and Scandinavia.

If the projections and trends presented in this assessment are borne out over the next five to ten years, this is very likely to have a serious impact on the future design of engineering structures in permafrost areas. However, engineering design should still be based on actual meteorological observations and a risk-based method.

The most important engineering considerations related to projected climate change include:

- risk-based methods should be used to evaluate projects in terms of potential climate change impacts;
- design air thawing and freezing indices should be updated annually to account for observed climate variations and change; and
- mitigation techniques such as artificial cooling of foundation soils should be considered as situations require.

Natural Resources

Climate impacts on oil and gas development have been minor so far, but are likely to result in both financial costs and benefits in the future. For example, offshore oil exploration and production is likely to benefit from less extensive and thinner sea ice because of cost reductions in the construction of platforms that have to withstand ice forces. Conversely, ice roads, now used widely for access to offshore activities and facilities, are likely to be useable for shorter periods and less safe than at present. The thawing of permafrost, on which buildings, pipelines, airfields, and coastal installations supporting oil development are located, is very likely to adversely affect these structures and the cost of maintaining them.

The coal and mineral extraction industries in the Arctic are important parts of national economies, and the actual extraction process is not likely to be affected much by climate change. However, climate change will possibly affect the transportation of coal and minerals in both a positive and negative sense. Mines that export their products using marine transport are likely to experience savings due to reduced sea ice and a longer shipping season. Conversely, mining facilities with roads on permafrost are likely to experience higher maintenance costs as the permafrost thaws.

Any expansion of oil and gas activities and mining is likely to require expansion of air, marine, and land transportation systems. The benefits of a longer shipping season in all Arctic areas, with the possibility of easy transit through the Northern Sea Route and Northwest Passage for at least part of the year, are likely to be significant. Other benefits are likely to include deeper drafts in harbors and channels as sea level rises, a reduced need for ice strengthening of ship hulls and offshore oil and gas platforms, and a reduced need for icebreaker support. Conversely, coping with greater wave heights, and possible flooding and erosion threats to coastal facilities, is likely to result in increased costs.

Climate Change in the Context of Multiple Stressors and Resilience (ACIA Chapter 17)

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Climate change occurs amidst myriad social and environmental transformations, some of which interact with climate change and help to determine its ultimate effects. The vulnerability of a human-environment system in the face of climate change, for example, depends upon multiple stresses on the system, the ways in which they interact with climate change, and the ability of the system to respond. Conceptual frameworks and analytical methodologies to examine these complex dynamics are now available. This chapter uses one such approach, namely vulnerability analysis, to carry out an initial phase of assessment for three case studies. Two of the case studies provide a cursory overview of multiple stresses, vulnerability and resilience for Sachs Harbour, NWT, Canada and coastal Greenland. The third case study provides a more in-depth analysis for Sámi reindeer herding in Finnmark, Norway. The case studies focus on multiple and interacting stresses acting on human-environment systems and the capacities of such systems to respond effectively. The stresses examined are climate change and concentrations of metallic and organic pollutants in the environment. Factors affecting vulnerability and resilience include coping and adaptive strategies, many of which reflect Arctic residents' cultural evolution through generations of experience in a highly variable environment. Largely in recognition of this latter point, this chapter focuses upon the livelihoods and well-being of indigenous peoples. It illustrates the importance of understanding stressor interactions; the need for methodologies that facilitate their characterization and analysis; and, most crucially, the need for vulnerability assessments to include the knowledge and viewpoints of local people and other decision-makers in the analyses.

Full assessments for communities in Sachs Harbour and coastal Greenland, require in-depth investigations into what the people living in these areas view as key concerns and how these residents perceive interrelations among, for example, natural resources and resource use, climate change, pollution, regulations, markets, and transnational political campaigns. This information will contribute to analysis and understanding of adaptation and coping, historically, presently, and in the future. For the Finnmark case next steps should include attaining a more complete understanding of interrelations among reindeer herding, climate change, and governance and how reindeer herders might respond to consequences arising from changes in these factors. This particular case highlights a number of other areas for future and/or continued investigation. These include analysis of the prospect that governmental management authorities or herders might respond to certain environmental and social changes in ways that could either enhance or degrade the reindeer herding habitat, and a more in-depth inquiry into extreme events and their implications for sustainable reindeer herding.

A comprehensive picture of the vulnerability and resilience of Arctic human–environment systems in relation climate change and other changes will benefit from further development of case studies, longer periods of longitudinal analysis, and more comprehensive research with interdisciplinary teams. Such assessments must include local peoples as full participants. Case studies should be selected to provide information across a wide array of human-environment systems and conditions so as to enable comparative work across sites. This will lead to improved understanding of resilience and vulnerability throughout the rapidly changing Arctic.

A Brief Summary and Synthesis of the Arctic Climate Impact Assessment (ACIA) (ACIA Chapter 18)

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Introduction

Chapter 18 of the Arctic Climate Impact Assessment (ACIA) provides a brief summary of the main conclusions of the 17 ACIA chapters. The chapter has three main parts. In the first part the conclusions are discussed chapter by chapter. Observed climate trends (Chapters 2 and 3, the latter on indigenous observations) are summarized. Projections of climate change over the 21st century, based on emission scenarios and computer model simulations (Chapter 4), are described, as are the observed and expected changes in stratospheric ozone and in UV radiation (Chapter 5).

Climate Change

Briefly, the observed temperature changes in the Arctic over the five-decade period from 1954-2003 range from a 2-3˚C warming in Alaska and Siberia to a cooling of up to 1˚C in southern Greenland. Winter temperatures are up to 4-5˚C warmer in Siberia and in the western Canadian Arctic. Composite five-model projections of annual temperatures show a fairly uniform warming of 2-4˚C throughout the Arctic by the end of the century, with a slightly higher warming of up to 5˚C in the East Siberian Sea. Summer temperatures are 1-2˚C warmer over land, with little change in the central Arctic Ocean, where sea ice melts each summer, keeping the ocean temperature close to 0˚C. Winter temperatures show the greatest warming of about 5˚C over land, and up to 8-9˚C in the central Arctic Ocean, where the feedback due to reduced sea ice is largest.

Arctic-Wide Impacts

The chapter summarizes Arctic-wide consequences of climate change, by examining the impacts on the environment (Chapters 6 on the cryosphere, Chapter 7 on terrestrial ecosystems, Chapter 8 on freshwater ecosystems, Chapter 9 on the marine system, and Chapter 10 on nature conservation). Impacts on people's lives are described in Chapter 11 on conservation and management, Chapter 12 on hunting and fishing, and Chapter 17 on multiple stress impacts. Impacts on economic sectors are described in Chapter 13 on fisheries, Chapter 14 on forestry and agriculture, Chapter 15 on human health, and Chapter 16 on infrastructure. These impacts cut across the entire Arctic and are generally not dependent on resolving regional details. For example, the timing, intensity, and magnitude of the melting of snow and ice under a warmer climate will have widespread implications for the entire Arctic and the global environment, even if these changes vary regionally.

Projected major large-scale environmental changes in the Arctic are illustrated in Fig. 1, which shows the existing and projected boundaries of sea ice, permafrost, and the tree line. The likely changes associated with these shifts are numerous and dramatic, as described in the chapters of the ACIA. For example, the map indicates that the tree line will reach the Arctic Ocean, as projected for most of Asia and western North America by the end of the century. This implies that there will be a near total loss of the tundra vegetation in these areas, with very important consequences for many types of wildlife. The consequences of permafrost thawing and sea ice reductions, as shown in Figure 1, have equally dramatic consequences.

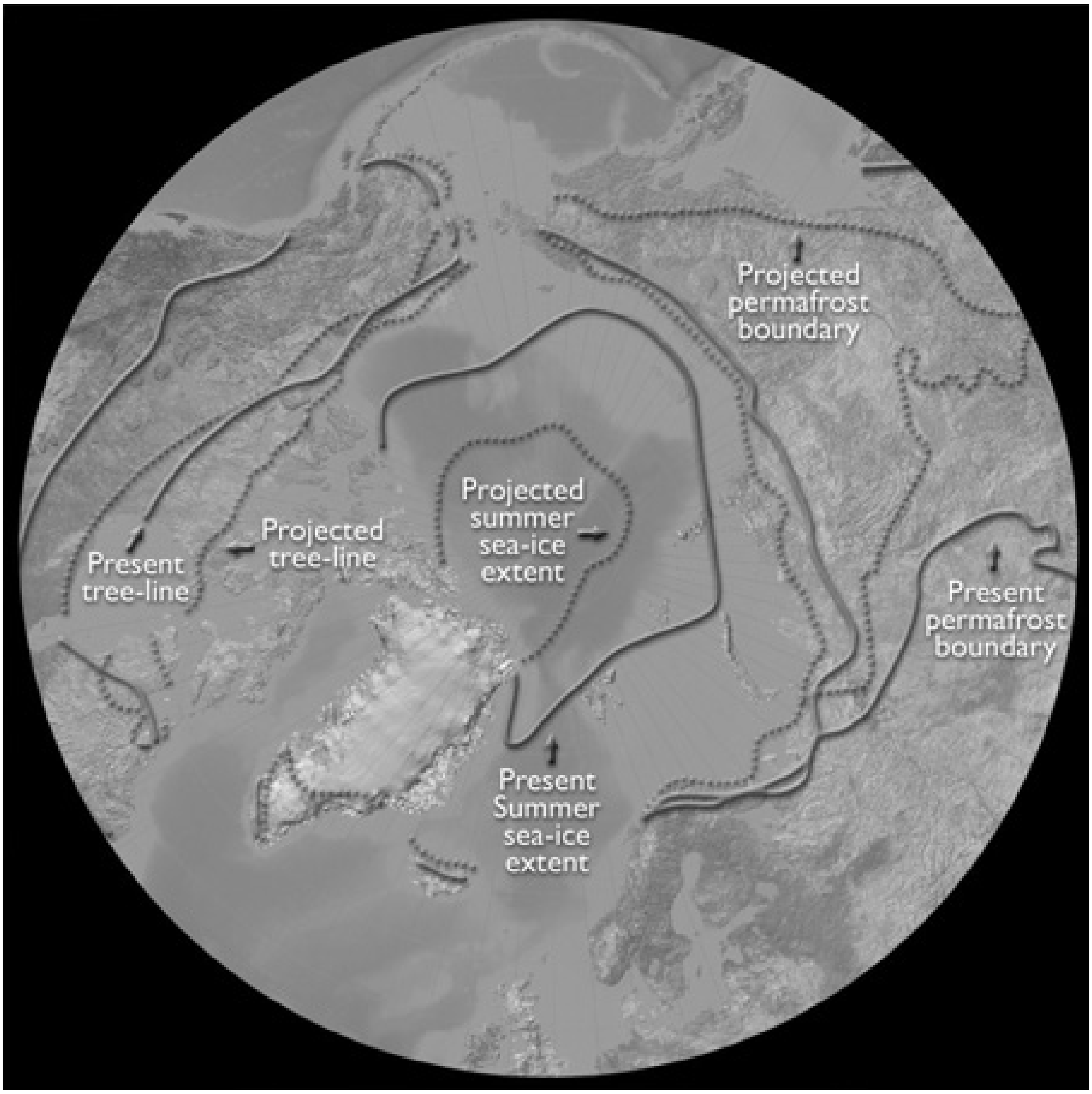

Figure 1. Map of the Arctic, showing present and projected boundaries of summer sea ice, permafrost, and the tree line. The projected changes will occur over different time periods. Changes in summer sea ice extent will occur by the end of the century, as projected by the five-model composite used by the ACIA. The projected changes in the tree line by the end of the century are from the Hadley model. The change in the permafrost boundary assumes that the present areas of discontinuous permafrost will be free of any permafrost in the future; this is likely to occur beyond the 21st century but it is not certain how long it will take.

Regional Impacts

The second part of the chapter is a synthesis of impacts on a local and regional basis, providing details on four different regions (or sub-regions) of the Arctic. This regional emphasis is necessary because the Arctic covers a large area and hence experiences significant regional variations in the changes in climate that will lead to different impacts and responses. Different regions also have different social, economic, and political systems, which will each be influenced in its own way, causing vulnerability and impacts to differ to a large extent on the basis of geopolitical and cultural boundaries. The four different regions in the Arctic for which results are presented are:

1. East Greenland, North Atlantic, northern Scandinavia, northwestern Russia
2. Siberia
3. Chukotka, Bering Sea, Alaska, western Canadian Arctic
4. Central and eastern Canadian Arctic, Labrador Sea, Davis Strait, West Greenland.

The rationale for selecting these four broad regions includes climatic, social, and other factors.

The third and final part of the chapter deals with broad crosscutting issues that are important in the Arctic. These are discussed in several chapters of the assessment, although usually in the context of the main topic of the chapters, and include the carbon cycle, biodiversity, and extreme and abrupt climate change.

Global Implications

Changes in climate and UV radiation in the Arctic will not only have far-reaching consequences for the arctic environment and its people, but also have to be viewed in a broader context since they will affect the rest of the world, including the global climate. These connections include arctic sources of change affecting the globe, e. g. feedback processes affecting the global climate, sea level rise resulting from melting of arctic glaciers and ice sheets, and arctic-triggered changes in the global thermohaline circulation of the ocean.

The Arctic is also important to the global economy. There are large oil and gas and mineral reserves in many parts of the Arctic, and arctic fisheries are among the most productive in the world, providing food for millions. Future openings of arctic shipping routes are likely to have benefits for the global economy and other North-South connections of consequence include the migratory birds, fish and mammals that are important conservation species in the South. The Arctic plays a unique role in the global context and climate change in the region has consequences that extent well beyond the Arctic.

The Changing Arctic Climate: Historical Observations and Recent Explanations

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Recent warming in the Arctic has similar magnitude as several historical events, but has greater geographic extent. Changes in atmospheric circulation play the crucial role.

Temperature anomalies in the last 15 years are unique in the Arctic instrumental record (1880—2003). Historically, there were regional/decadal warm events during winter and spring in the 1930s to 1950s, but meteorological analysis shows that these surface air temperature(SAT) anomalies are the result of intrinsic variability in regional flow patterns, as contrasted with the Arctic-wide Arctic Oscillation (AO) influence of the 1990s. Long-term changes in SAT from 59 weather stations north of 64°N are most evident in spring, with cool temperatures before 1920 and Arctic-wide warm temperatures in the 1990s. The recent decades are unique in having the greatest longitudinal extent of SAT anomalies and in their associated weather patterns.

Figure 1 shows the time evolution of surface air temperature anomalies for the 59 weather stations (x-axis) and over time (y-axis) for December—January and April. Figure 2 shows polar projection maps of surface air temperature and sea level pressures for particular years and seasons. Only the spring in the 1990s has Arctic-wide warm anomalies and an Arctic-wide influence from low sea level pressure.

These changes are primarily driven by changes in atmospheric circulation, and thus are subject to north/south gradients in hemispheric radiative forcing. Atmospheric circulation is sensitive to changes in radiative forcing in the sub-tropics from volcanic aerosols, insolation cycles and CO2 increase. Temperature advection in the trough-ridge structure of the AO in the North Atlantic establishes wintertime temperature anomalies in the adjacent regions, while the zonal/annular character of the AO in the remainder of the Arctic must break down in spring to promote meridional temperature advection.

Figure 3 shows the global temperature anomalies in the winter following the eruption of Mt. Pinatubo (Robock 2003). Note the warm anomalies over northern Eurasia; north/south differences in radiative forcing favor the positive phase of the North Atlantic Oscillation, which then results in wintertime warming. Figure 4 shows a conceptual model of what factors influence changes in Arctic atmospheric circulation. The circulation itself is very chaotic involving feedbacks between storms and the mean flow field (polar vortex). However, the statistics of the polar vortex can be influenced by subtropical processes and by feedbacks within the Arctic.

Change is likely to be irreversible over the next decades, as the Arctic has locked in 20% changes in tundra and sea ice reduction, northward shifts in ocean temperature, and ozone chemistry. While many of the results noted in the ACIA report can be traced to shifts in atmospheric circulation, their cumulative effect over the last two decades has produced changes in surface conditions felt by the atmosphere, such as albedo, surface temperature, and moisture and heat fluxes; the long-term trends in many Arctic variables support the concept that current conditions are moderating the former year-to-year range of Arctic weather, and thus provide persistence to current trends. Figure 5 shows the Arctic Oscillation index. Note the return to near normal values after 1996. A paradox is that the broad changes for the Arctic noted by ACIA are continuing, while atmospheric circulation indices have returned to near normal. Please consult the online version of the extended abstract for color versions of the figures. More complete information is found in Overland et al. (2004a) and Overland et al. (2004b).

We appreciate the support of the NOAA Arctic Research Office

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Figure 1

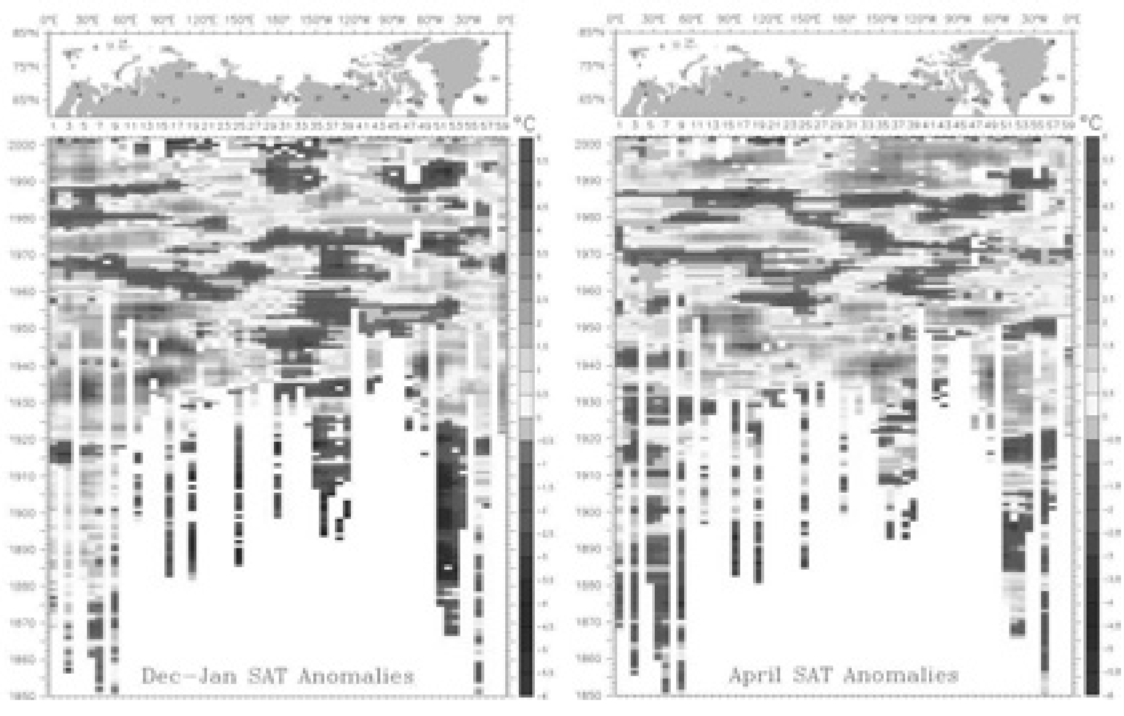


Figure 2

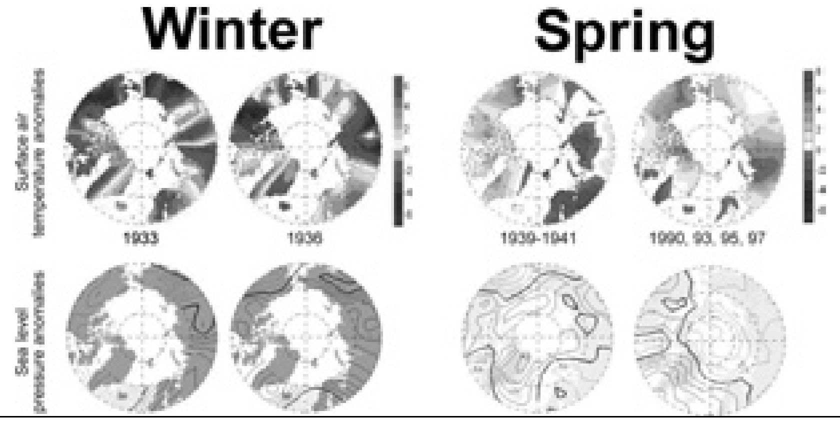


Figure 3

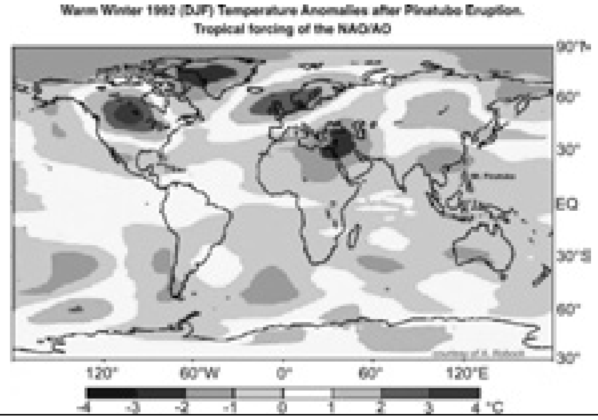


Figure 4

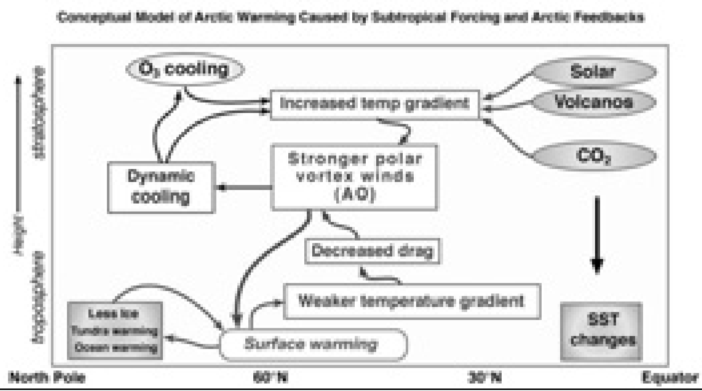
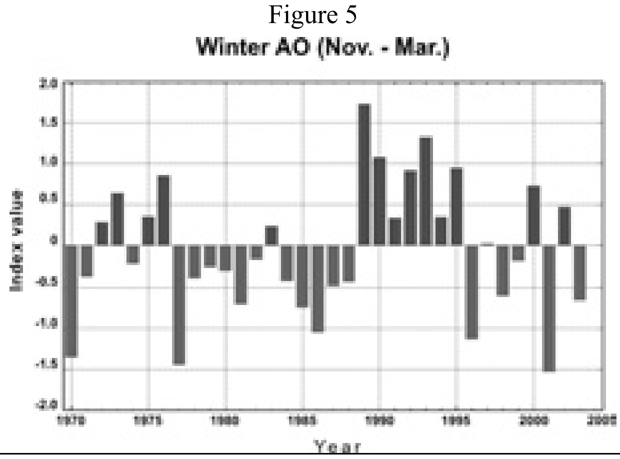


Figure 5



Spatial and Temporal Mapping of Temperature Variability in Iceland since the 1870's

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Abstract

Using data from the archives of the Icelandic Meteorology Office (IMO) timeseries of monthly mean temperature anomalies (from 1961 to 1990 climatology) have been constructed for several stations. This procedure has been applied to 10 weather stations with records starting in the late 1890's. In one case discontinuous records extend as far back as the early 1820s. Furthermore, these anomalies have also been calculated for more than 80 stations that were in continuous operation between 1961 and 2000. Using this data gridded maps of monthly anomalies were constructed. These maps provide a convenient way to examine changes in temperature in Iceland in the last century. Calculating differences of pentad means, linear trends and the EOFs of these maps shows the dominant patterns of temperature change and calculating the areal average of the temperature anomaly yields a temperature anomaly timeseries. Using series of maps thus obtained, we examine the spatial and temporal characteristics of temperature change in the Icelandic records.

Introduction

When the Icelandic Meteorological Office (IMO) was founded in 1920 it inherited an observation network that had been maintained by the Danish Meteorological Institute since its inception in 1872. The number of stations in this network varied, but was usually between 15 and 20. The IMO network was expanded in the next decades, and during the 30 year period from 1961 to 1990, more than 80 manned weather stations were simultaneously in operation (see Figure 1). Of these stations, a few have been in continuous operation since the late 19th century (solid circles in Figure 1), but several more stations from the 1920s onwards (triangles in Figure 1).

For each station, monthly anomalies from 1961 – 1990 climatology were calculated. The monthly station anomalies were then interpolated to a grid using the Kriging interpolation method [1]. This work was done separately for the period 1961 to 2000 using the dense network of stations, and also starting in 1898 using a network of 10 stations. The dense network provides a good estimation of the areally averaged temperature changes in the last 40 years of the 20th century, and the 10 station network can be used to calculate areally averaged changes in the mean temperature throughout the 20th century. The two timeseries compare favorably in the period of overlap (see Figure 2).

Results

Figure 2 shows timeseries of areally average temperature anomalies calculated using 1961 – 1990 as a reference period. The figure shows the timeseries from Stykkisholmur, which has reconstructed data from 1823 to 1845 and continuous measurements thereafter [2,3]; from 1898 onwards the figure shows the areal average of a 10 station network, and from 1960 an average of 85 stations.

First, there is an amazing agreement between the data from Stykkisholmur and the areally averaged curves. This shows that for annual averages, one station can be a good indicator of temperature changes for a larger region (the dimensions of Iceland are roughly 300 by 500 km), however, one should note that the annual curves average out seasonal and spatial variability. Second, the extremes in the early part of the record from Stykkisholmur are suspicious (especially the warming observed in 1828 which may be an artifact of the way the thermometer is known to have been mounted).

In examining the figure, one is immediately struck by the scale of the warming during the 1920s and 30s. The lowest annual temperatures from 1925 to 1945 are similar to temperatures that were previously the warmest observed. There is a cool period in the late 1960s which coincides with the years of the Great Salinity Anomaly (GSA), when sea ice was prevalent during late winter along the north coast, and there is another cold period in the late 1970's with 1979 being the coldest year of the 20th century. Incidentally, this winter was the last period with heavy ice conditions during the 20th century. There is a warming trend during the last 20 years of the record.

The spatial characteristics of this recent warming trend are shown in Figure 3. It shows the annual mean temperature from 1996 to 2000 minus the average from 1976 to 1980. The figure clearly shows that in the last decades of the 20th century, all of the country warmed, but the warming was greatest in the north-eastern part. Similar spatial pattern was seen for seasonal averages. Generally speaking, the predominant winds in Iceland are either south-westerlies or north-easterlies. A pattern such as that seen in Figure 3 is consistent with either an enhanced frequency of SW winds which would warm the country as a whole, but preferentially warm the NE due to Föhn effects, or the pattern could be due to a reduced frequency of NE winds, but these tend to cool the northern coast. The two mechanisms do obviously not exclude each other, but in general this pattern resembles the one eigenmode for the temperature field in Iceland, which is a SW-NE dipole. The map in figure 3 is produced using all the stations shown in Figure 1, but a similar map is obtained from the 10 station network (filled circles in Figure 1).

The spatial pattern of warming during the early part of the 20th century is shown in Figure 4. The warming is clearly greater during this period than for the period shown in Figure 3. In both cases, however, all of the country warms, but the warming is enhanced in the NE part of the country. However, the warming in Figure 4 is greater along most of the northern coast, whereas the results in Figure 3 show enhanced warming predominantly on the NE coast. Examining the period 1916 to 1940 in through differences of pentad means revealed that between 1916-20 and 1921-25 the warming was predominantly along the north coast, and only later acquired a SW-NE character.

Discussion

Timeseries of temperature change in Iceland since the 19th century show a period of rapid warming following the 1920s. Similar warming is observed in global averages, but in Iceland the temperature change was greater and was more abrupt. From the 1950s temperatures in Iceland had a downward trend with a minimum reached during the GSA years in the late 1960s and again in 1979. Since the 1980's, Iceland has experienced considerable warming, although temperatures at the end of the 20th century had not reached values comparable to those observed in the 1930s.

Comparison of the spatial pattern of the warming in the 1920s and 1930s with temperature changes in the last 20 years, shows systematic differences. Recent warming has spatial characteristics that resemble the first eigenmode of the temperature field in Iceland (i.e., a SW-NE dipole), whereas the rapid warming in the early part of the 20th century is more complex. During the first part of the rapid warming it is greater along the north shore than along the south shore (has an N-S character to it) and only later acquires an SW- NE character. The N-S pattern may be due to the climatic influences of sea ice. During the GSA years when winter sea ice was prevalent along the north coast, the cooling on the north coast far exceeded that further south. In 1918, exceptional amounts of sea ice occurred along the Icelandic coast, and the early phase of the warming that followed is likely to reflect a shift from sea-ice conditions to more normal conditions. The air temperature in Iceland is greatly influenced by advection of warmer air from the south [4,5]. Proximate causes for differences in warming patterns can thus further be linked to differences in the large scale circulation patterns.

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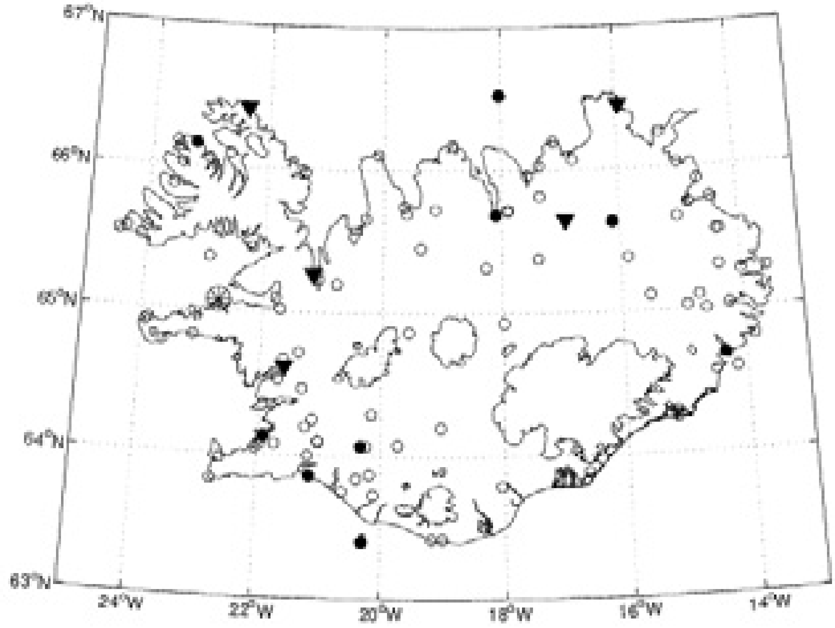

Figure 1. Station network. All stations on the figure were in operation between 1961 and 1990. The stations marked with a filled circle where operational throughout the entire 20th century. The station at Stykkisholmur, marked with an asterix has data since 1823.

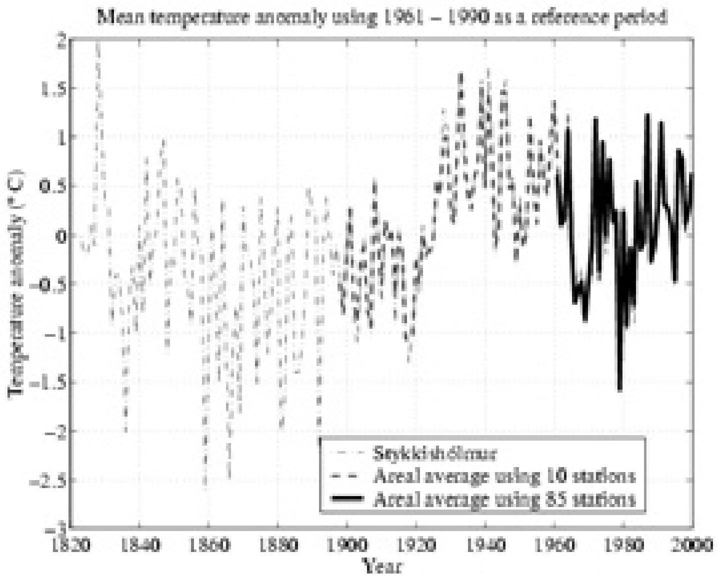

Figure 2. Temperature variations in Iceland since the early 19th century. Shown are annual anomalies from 1961 to 1990 climatology. The thin line shows results from Stykkisholmur, the thicker dashed line shows the areal average obtained using 10 stations that were in operation during all of the 20th century. The solid line shows the results obtained using more than 80 stations.

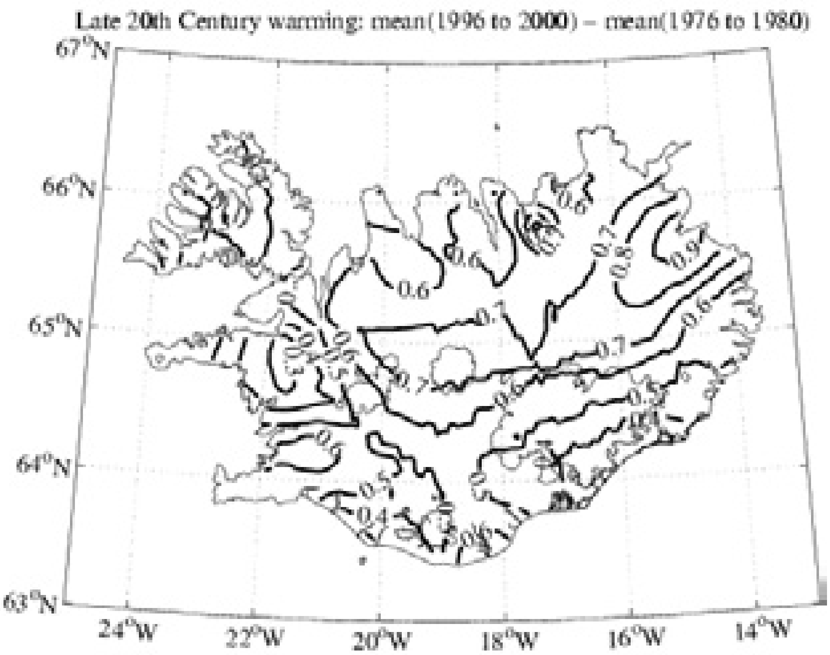

Figure 3. Temperature change in Iceland during the last decades of the 20th century. The figure shows the 1996 to 2000 average minus the 1976 to 1980 average.

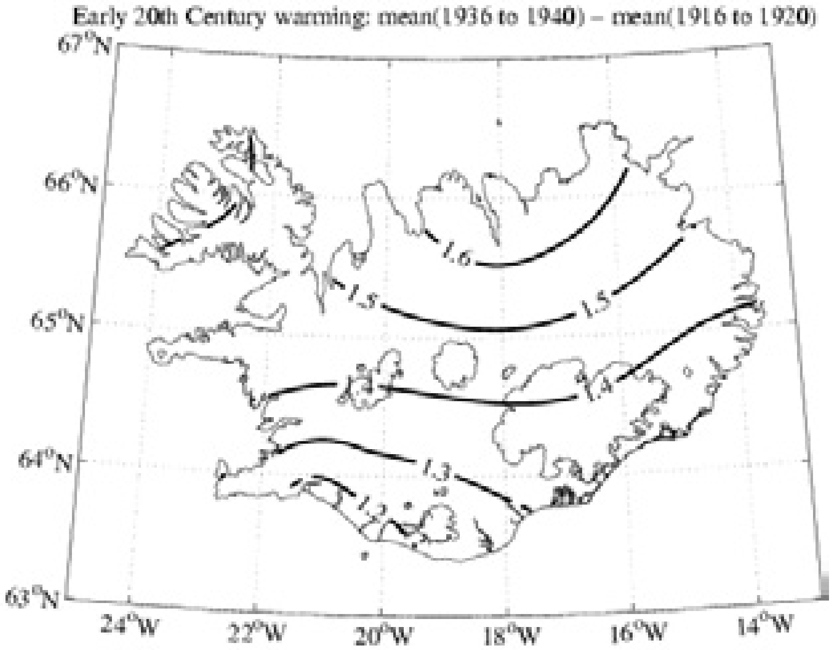

Figure 4. Temperature change in Iceland during the rapid warming phase in the first half of the 20th century. Shown is the 1936 to 1940 average minus the 1916 to 1920 average, The data used is comes from the 10 station grid.

Joint Roles of the Panarctic Shelf Break and Retreating Summer Ice in Arctic Warming

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[3] (Deceased) Woods Hole Oceanographic Institute, Woods Hole, MA, USA

Large continental shelves comprise about 50% of the surface area of the Arctic Ocean, and play a key role in establishing property distributions within the arctic basin (Aagaard et al., 1999). For a great part of the year the ocean is covered by ice, and this significantly affects hydrographic conditions and the dynamics of wind forcing. As such, the efficiency of shelf/basin exchange (SBE) in the Arctic Ocean is strongly moderated by the location of the ice edge relative to topography, and this in turn affects heat, salt, nutrient and carbon budgets. Summer melt-back, which proceeds from the coast seaward, currently allows only brief exposure of the ocean surface to upwelling or downwelling favourable winds. Idealized model calculations (Carmack and Chapman, 2003) suggest that upwelling-favourable winds generate little SBE so long as the ice edge remains shoreward of the shelf-break, but abruptly increases when the ice edge retreats beyond the shelf break (Figure 1). But the ice cover is changing (Comiso and Parkinson, 2004). Under scenarios of climate warming used in the ACIA analysis, both the extent and duration of summer melt-back are predicted to increase, so that this 'tipping point' may routinely be reached by the middle part of the 21st century. Here we discuss this condition from a panarctic perspective and note potential consequences to SBE and new primary production. To do this, we use NCEP re-analysis wind field data and existing nutrient data to estimate the potential increment in new productivity that may follow from a reduction in summer ice extent.

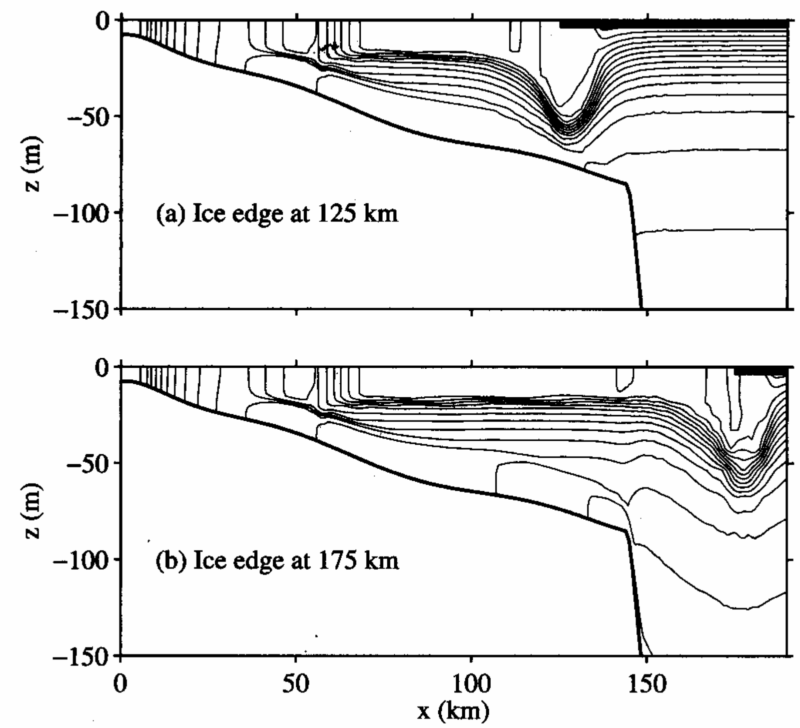

Figure 1: Model results for upwelling favourable winds blowing parallel to the coast for 15 days with a stationary ice cover located (a) 87 km and (b) 125 km from the coast (from Carmack and Chapman, 2003).

To obtain flux estimates onto the shelf we use the NCEP reanalysis wind field data from grid points near the mid-point of the shelf-break for each shelf sea. Wind-stress is calculated from $\tau = \rho_a C_D|\mathbf{U}|\mathbf{U}$, where τ is wind-stress, $\rho_a = 1.2$ kg/m^3 is air-density, $C_D = 0.0015$ is a drag coefficient and U is the wind velocity (Figure 2). Ekman transport off the shelf is then found from $T_E=\tau/\rho_0 f$, where T_E is Ekman transport, $\rho_0 = 1000$ kg/m^3 is a reference density for seawater and f is the Coriolis parameter. For the purposes of this rough estimate we suppose a three month period of open water at the shelf break (July-September) and further assume that the synoptic, upwelling-favourable events are cumulative, and ignore downwelling events (but, see below). The flux of upwelled water across any given shelf-break is then set equal to T_E as computed from upwelling-favourable winds for a three-month summer period.

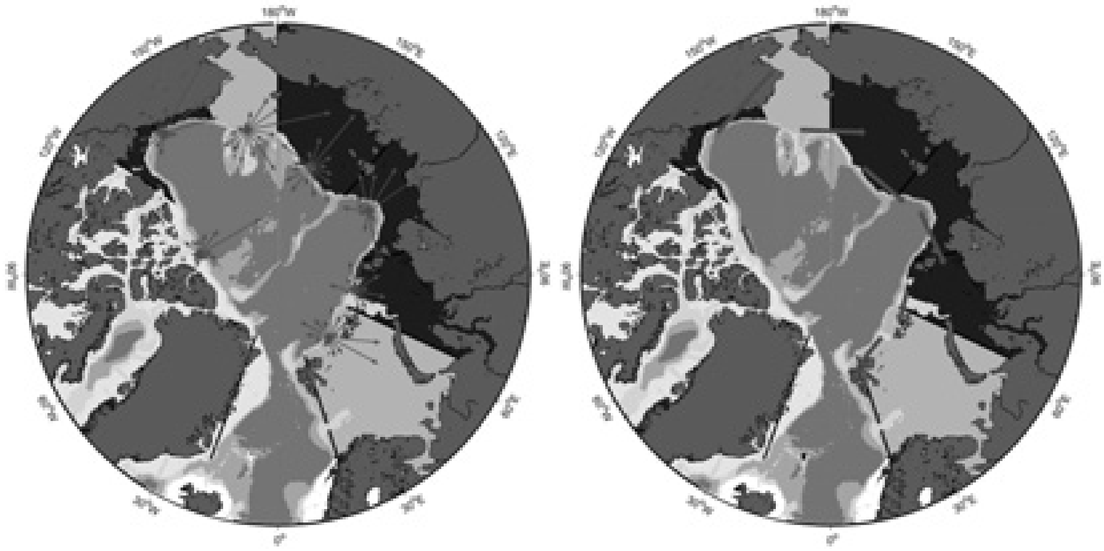

Figure 2: (a) Wind-stress during 'summer' of 1998 at selected NCEP grid points located near the mid-point of shelf-breaks for individual seas. (b) Mean of upwelling-directed wind-stress for 'summer' of 1998 at the same locations.

To estimate primary productivity due to upwelling, we examine nutrient data from various sources (Wilson and Wallace, 1990; Wheeler et al., 1997; McLaughlin et al., 2004); NO_3 was assumed to be the limiting nutrient. For the purpose of this rough calculation we take NO_3 values immediately seaward of the shelf break to be 12 and 15 mmol m^{-3} for the Eurasian and Canadian basins, respectively. Upwelled nitrate is then calculated as the product of $\boldsymbol{T_E}$ times the offshore concentration. Upwelled nitrate is assumed to reach the surface layer, be dispersed equally across the surface area of individual shelves and be completely utilised in new production; the latter is calculated here using the Redfield ratio of 106:16.

Table 1 compares present measurements of new production with estimates of the increase in new production (ΔNP), resulting from upwelling, for each shelf using NCEP data from 1998. (This year, one of strong positive Arctic Oscillation (AO), was chosen because climate warming scenarios suggest that the Arctic may tend towards this state.) Two estimates of ΔNP were calculated: one using the mean upwelling-directed wind-stress and one using the difference between the mean upwelling and the mean downwelling-directed wind-stress; but only the former is shown in Table 1.

Large differences in ΔNP are seen among the various shelf seas due to variations in (a) magnitude of upwelling, (b) offshore NO_3 value, and (c) the width of individual seas; the latter had the largest effect on our estimates. In the Canada Basin, the narrow shelves of the Beaufort and northern Canadian Arctic Archipelago give the largest increases in new production per unit area whereas the wide shelves of Chukchi and Eurasian basin result in low

Shelf	Shelf Area 10^3 km^2	Shelf Length km	NP gC m^{-2} y^{-1}	Ekman Flux m^2 s^{-1}	Nutrient Flux mmol m^{-2} y^{-1}	ΔNP gC m^{-2} y^{-1}
Barents	1512	771	16*	0.16	7.79	0.62
Kara	926	555	7 - 12	0.15	8.15	0.65
Laptev	498	863	6 - 10	0.25	40.81	3.24
East Siberian	987	1018	6 - 10	0.24	28.34	2.25
Chukchi	620	771	5 - >160	0.29	42.14	3.35
Beaufort	178	1140	7 - 17	0.38	284.30	22.60
North CAA	146	2065	5 - 10	0.13	220.86	17.56

* For Barents Sea north slope

Table 1: New production estimates for Arctic shelf seas taken from Sakshaug (2003) and estates of the increase in new production due to upwelling wind-stress during ice-free conditions.

values. The estimated wind-stress is also a factor, largest upwelling wind-stress being found in the Beaufort which combined with the relatively narrow shelf gives the largest estimate of increase in new production. Inclusion of downwelling wind to the wind-stress estimate causes an even greater difference between the Beaufort and CAA and the remaining shelves. Relatively persistent upwelling winds over the Beaufort and Chukchi shelves give larger estimates of mean wind-stress whereas in other areas wind-stress estimate is reduced to close to zero or is negative.

It is crude to assume that all upwelled nitrate reaches the euphotic zone uniformly over the shelf. Indeed, vertical exchange in Arctic seas is strongly constrained by salt stratification and the flux of nitrate to the surface is likely achieved either near the coast, which requires the deep water transit from the shelf break to the coast, or is mediated by vertical mixing, as the nutrient rich water floods the bottom of the shelf. In either case smaller scale processes, such as coastal upwelling, topographically enhanced vertical mixing due to tides, canyons and variations in shelf direction, can be anticipated to be important factors to onshore and vertical nitrate flux. It is perhaps the efficiency of these localised processes that is the controlling factor. Our upwelling fluxes are also reliant on assumptions concerning air-ice-water coupling and internal ice-stress (cf. Carmack and Chapman, 2003).

In a panarctic sense it is useful to distinguish among “inflow” shelves, “interior” shelves and “outflow” shelves *viz* their response to enhanced upwelling. On inflow shelves incoming water from the Atlantic (Barents Sea) and Pacific (Bering & Chukchi seas) supply nutrients independent of upwelling. Interior shelves (Kara, Laptev, East Siberian and Beaufort) – though fed by the major arctic rivers - are strongly affected by SBE exchange processes. The outflow shelves along the east coast of Greenland and various passages of the Canadian Arctic Archipelago allow passage of Arctic waters back into the North Atlantic, and thus draw water from the offshore basins independent of upwelling. The estimates provided here are likely more applicable to the interior shelves.

Acknowledgement

We would like to acknowledge Dr. Robie Macdonald, who first wrote about the difference between a good ice year and a bad ice year on the Canadian Shelf of the Beaufort Sea, and Dr. Terry Whitledge, who first ask us to think about a link between the shelf-break and climate change.

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The Ob River: Is there Arctic Inflow Increase?

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Introduction

It is known importance of the Arctic for global climate system. Also it is well known that hydrologic cycle is one of main component of the arctic climate and changes in the terrestrial hydrologic budget influence the extent of sea-ice cover, freshwater transport into the North Atlantic and deep ocean convection. The annual freshwater inflow of arctic rivers reaches a total of 3300 km^3 (Stein, 2000).

It notes increase of annual precipitation over the northern Hemisphere during the last 50-70 years, especially for the cold seasons (Serreze et al., 2000). The same is impartially for the West Siberia (Agafonov et al., 2004). Also some authors note that the average annual discharge of fresh water from 6 largest Eurasia rivers to the Arctic Ocean increased by 7% from 1936 to 1999 (Peterson et al., 2002).

The Ob river is one of the great rivers of the northern Hemisphere (the Ob + Irtysh channel length is 5410 km; catchment basin is about 3 millions km^2, floodplain area is 75 000 km^2, average runoff is 429 km^3 yr^{-1}) and transports from south to north an amount of heat of more than 10^{10} MJ. The Ob plays a crucial role for climate of the floodplain and adjacent uplands during the ice-free period. There are both cooling and warming effects of the Ob's streamflow to air temperature (Agafonov and Mazepa, 2001).

Materials and Methods

Records of annual precipitation over the Ob catchment basin southward from 60°N and the daily water Ob levels of the ice-free period in 5 gauge stations (Khanty-Mansiisk, the Irtysh river, 60°58′N, 69°04′E, 1200 km from the Ob estuary, 1894-1995; Surgut, 61°15′N, 73°30′E, 1502 km from the Ob estuary, 1894-1993; Oktyab'rskoe, 62°27′N, 66°03′E, 907 km from the Ob estuary, 1922-1996; Muzhy, 65°23′N, 64°43′E, 450 km from the Ob estuary, 1934-2002; Salekhard, 66°31′N, 66°36′E, 280 km from the Ob estuary, 1934-1996) for the last century were analyzed.

There are no water discharge measurements on the foregoing gauges (except Salekhard) and we used daily water levels to estimate the Ob flow because of correlation between a hydrograph of water level and a water discharge hydrograph is very high for years with low as well high water discharge (r = 0.97 for the Salekhard gauge).

Really, more than 80% of the Ob's runoff supplies from the southern part of the Ob catchment basin (2.72 millions km^2). Cold season precipitation records from October to May (CSPR) from 61 meteorological stations on that area were compared against the total daily water levels (TDWL) of the ice-free period of the Lower Ob river.

For precipitation analysis the Ob catchment basin was shared 4 basins of the large confluents out: the Tobol (426x10^3 km^2, 12 meteorological stations), the Ishim (177x10^3 km^2, 6 meteorological stations), the Irtysh (1643x10^3 km^2, 24 meteorological stations), the Upper and the Middle Ob (1047x10^3 km^2, 19 meteorological stations).

Results and conclusions

There is significant positive correlation (r = 0.37-0.67) between the CSPR of the Tobol, Ishim, Irtysh and the Upper and the Middle Ob river basins. Also they display positive precipitation trends since 1950th (Fig. 1). Correlation between the TDWL for the ice-free period of the Lower Ob and the average CSPR on the Upper and Middle Ob, the Irtysh, the Tobol and on the Ishym basins is 0.26, 0.52, 0.26, 0.36, respectively.

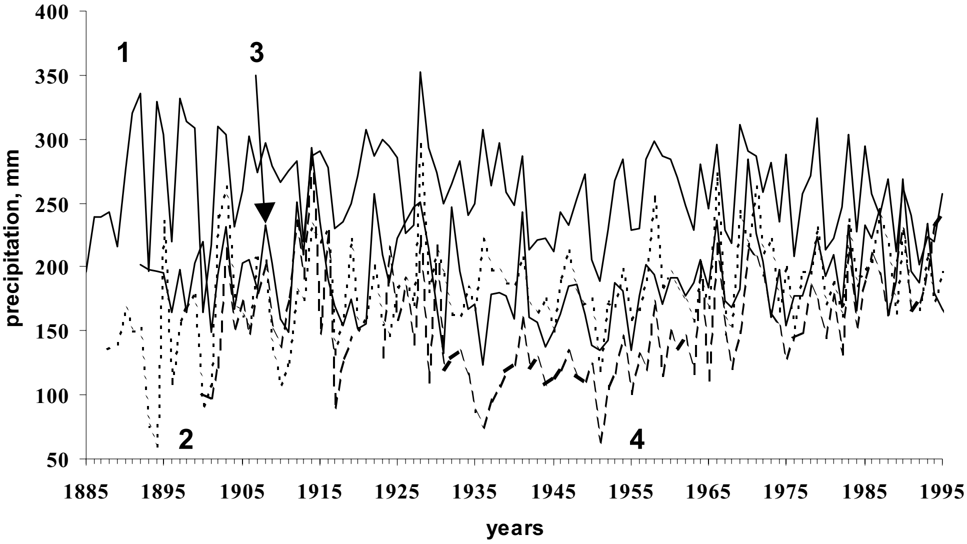

Fig.1. Average cold season precipitation from October to May (CSPR) on the Upper and Middle Ob (1), on the Irtysh (2), on the Tobol (3), on the Ishym (4) basins.

Significant positive correlation (r = 0.38) between the summary CSPR of the four basins and the TDWL of the Lower Ob river (Oktyab'rskoe gauge) was revealed. At the same time, there are differences in the long-term dynamics for the both parameters: positive trend for precipitation and negative one for TDWL (Fig. 2). What is more, the decrease of the TDWL is observed on the whole 4 gauges regardless of the fact that there is increase of the CSPR on the whole Ob catchment basin.

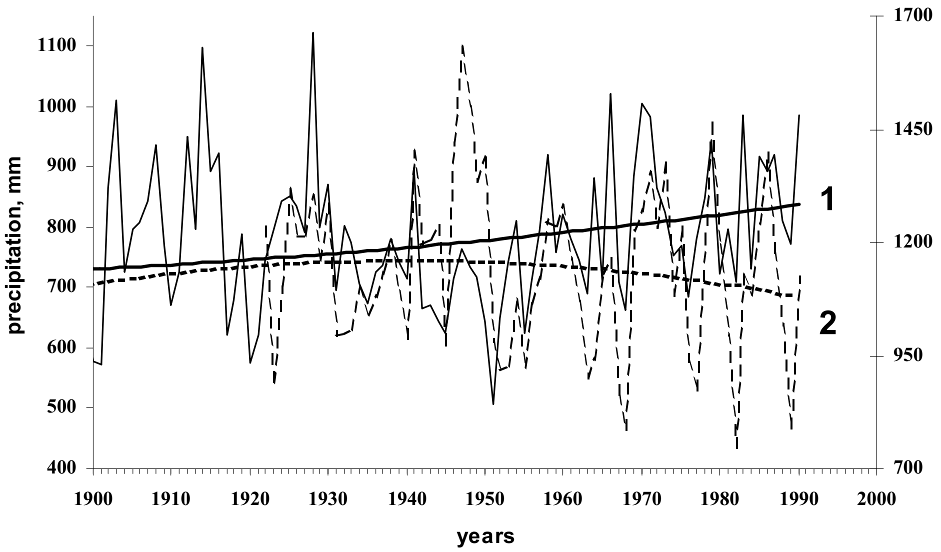

Fig. 2. Summary CSPR of the four basins (1) compared against the TDWL (2) of the Lower Ob (the Oktyab'rskoe gauge station) and their trends by polynomial function.

Deferent tendencies for the annual maximal water levels (AMWL) are observed on the gauges. Surgut, Khany-Mansiisk and Oktyabr'skoe display obvious decrease of the AMWL whereas Muzhy and Salekhard show weak apparent increase tendency (Fig. 3). Perhaps, this phenomena is explained by distribution of extensive floodplain which is the vastest on over the Ob and reaches here up to 60 km from the west to the east. Moreover, extensive peatlands are widespread in this part of the West Siberia and they can control drainage regime of the region too. Also dates of the AMWL had a tendency to come earlier from year to year during a period of records on the whole gauges (Fig. 4).

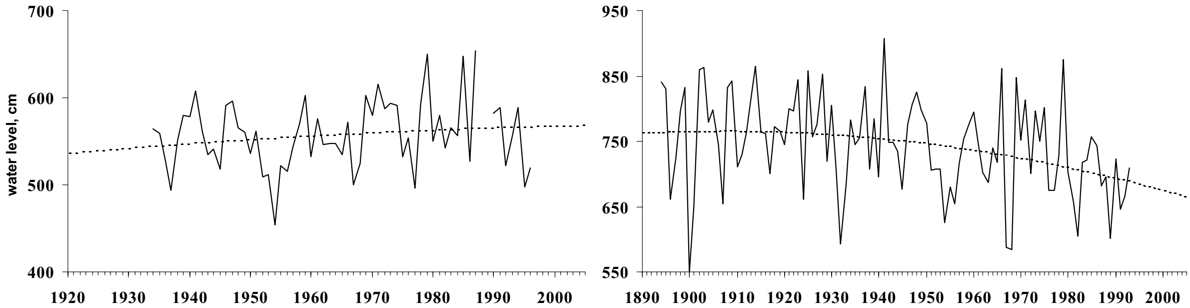

Fig. 3. The maximal Ob water level of the ice-free period in Salekhard (left) and Surgut (right) and their trends by polynomial function.

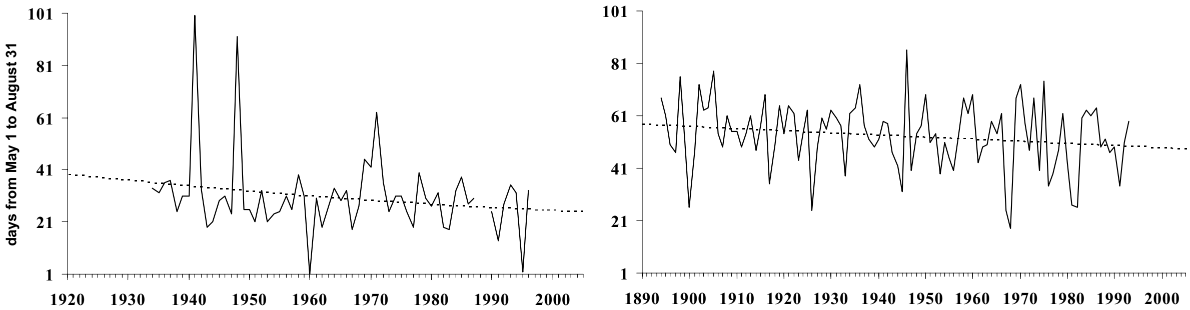

Fig. 4. Dates of the maximal water level for Salekhard (left) and Surgyt (right) gauges and their trends by polynomial function.

Other hydrological events changed during the last century too. Breaking-up dates come earlier from year to year on over the Ob river basin. Quite the contrary freeze-up dates come later from year to year and duration of the ice-free period is extended. At the same time, it is to be noted that a submergence duration of the Ob floodplain either do not changes or has a tendency to decrease on the whole basin.

Thus, our results don't allow to affirm that one of the largest rivers of the northern Hemisphere displays the inflow increase to the Arctic Ocean regardless of the fact that there is some increase of the cold season precipitation on the whole Ob catchment basin. From our point of view there are several causes of this phenomena. One of theirs is, perhaps, an physical evaporation increase on the whole basin duo to significant increased air temperatures (Moritz et al. 2002). Other important cause is connected, most likely, with the changes of spatial and age structure of forest cover over the Ob basin which have a strong influence on physical evaporation and redistribution of precipitation. Illustration for these suppositions is the changes of breaking-up, freeze-up and flood crest dates which were determined for the Ob river.

Acknowledgement

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Linkage between Sea-ice Distribution and Snow-precipitation may considerably affect Terrestrial Ecosystems in Future High Arctic Climates

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC)'s Third Assessment Report (TAR) (2001) gives projections for global-mean warming from 1990 to 2100 within a range of 1.4º to 5.8ºC in the case that no measures are taken to limit climate change. Further, research demonstrates that based on this assumption, a global-mean temperature increase around 3ºC by the end of the 21st century is the most likely; and that probabilities of global-mean warming values at both the high and low ends of the TAR range [1.4ºC , 5.8ºC] are very low (Wigley and Raper, 2001). General Circulation Models (GCM) predict global warming to be most pronounced at high latitudes, especially during winter time when temperature increases of up to 6ºC can be expected by the end of the 21st century (Hadley Centre, Max Planck Institute of Meteorology).

Arctic ecosystems are strongly influenced by snow cover and temperature, and may be expected to be markedly altered by climate change (Phoenix and Lee, 2004; Stone et al., 2002; Weller, 1998). Besides increases in winter temperatures in the Arctic, decreases in sea-ice extent are expected to occur correspondingly (Johannessen et al, 2004), which may significantly influence the regional climate. Here we present an empirical analysis from Northeast Greenland, which shows that reduced amounts of sea-ice in the region will most likely lead to increased snow-precipitation. Due to a shorter snow-free season this might have consequences for High Arctic ecosystems that at a first estimate are unexpected in a future warmer climate.

2. Methods and Analysis

We have calculated end-of-winter snow-precipitation amounts at two different scales – local and regional, using two different modeling approaches: The first approach, which is used at local scale (covering 12 years: 1988-2000, except 1990) exploited data from Zackenberg Research Area (ZRA), Northeast Greenland (74.5ºN, 21.6ºW) obtained during the melting season (June-August). It is based on snow cover maps derived from remotely sensed image data, melt energy inferred from daily mean air temperatures, and measured snow depths. The image data types are digital orthophotos covering approximately 17 km^2 (Hinkler et al., 2002), and high resolution satellite images (Landsat Thematic Mapper (TM) & SPOT High Resolution Visible (HRV)). Daily mean temperatures are from automatic weather stations at Zackenberg and Daneborg (located 23 km southeast of Zackenberg). The second modeling approach is used at regional scale and deals with relative humidity and temperature (Liston and Sturm, 1998) during winter time (October-May). It simply assumes that snow-precipitation falls when the air temperature is below freezing and the relative humidity is greater than 80%. For this purpose we used daily values (air temperature and relative humidity) during 1981-2000 of a 2.5º×2.5º lat-long-grid-cell from the National Centre for

Environmental Prediction (NCEP) reanalysis project. The spatial coverage of the grid-cell is approximately 21,000 km^2 (Fig. 1). The least-squares fit, reveals that the local snow-precipitation at Zackenberg is significantly correlated with what is modeled at a much larger scale. However, it also reveals that local snow-precipitation in some winters can differ significantly from regional precipitation. This is probably because the area is characterized by strong topography, which complicates the local wind patterns and thereby also precipitation distribution.

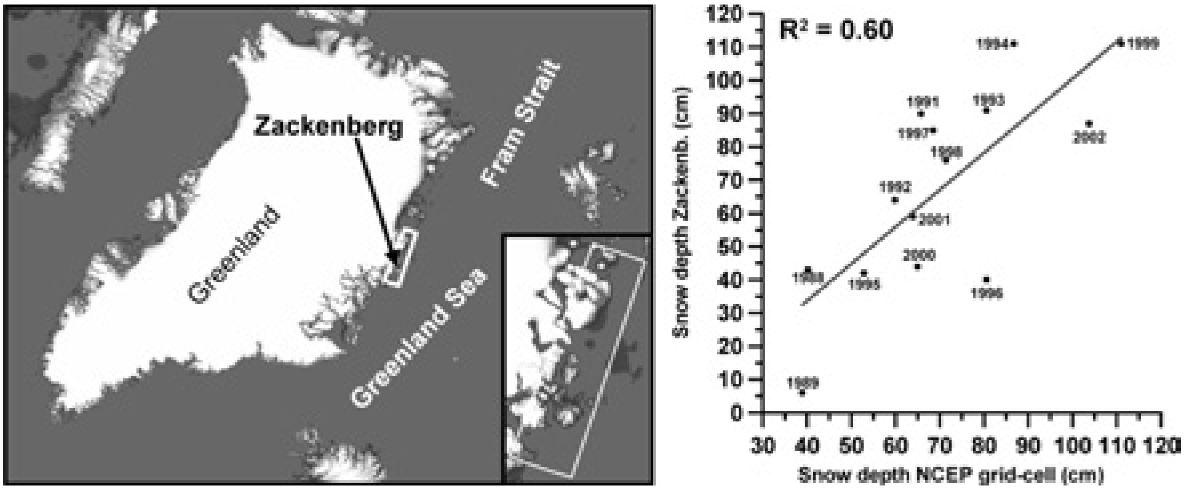
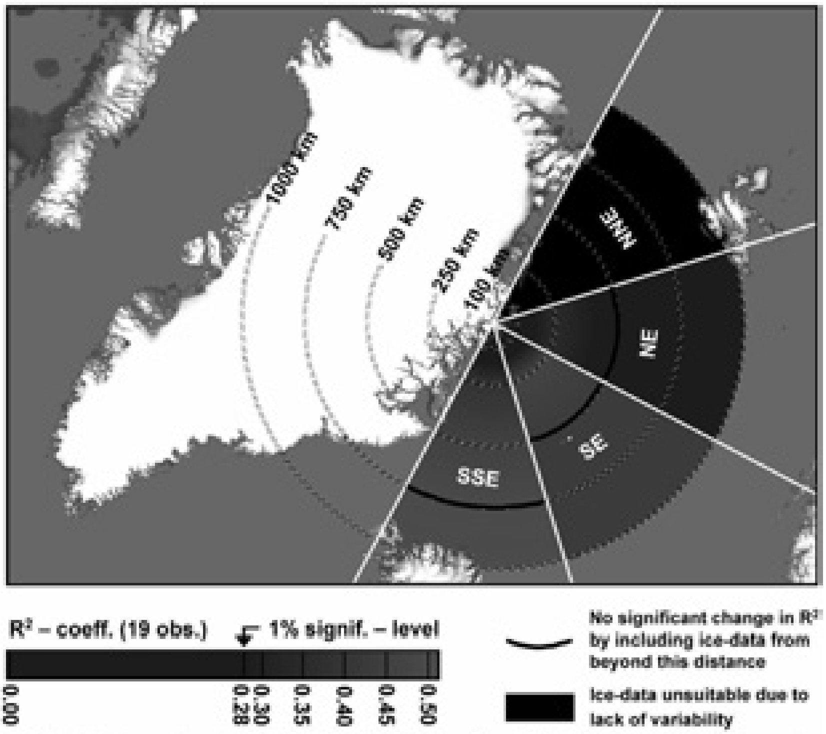


Fig. 1. (Left) Location of the Zackenberg Research Area (red cross). The rectangular area indicated by white lines corresponds to the 2.5º×2.5º lat-long grid cell (21,000 km2) from the NCEP reanalysis data, which includes the Zackenberg Research Area (ZRA). (Right) Modeled snow depths: ZRA versus entire area in NCEP grid cell (Normalized to Zackenberg, 1999).

To analyze the relation between duration of periods with extensive sea-ice within the Greenland Sea and snow-precipitation at Zackenberg we analyzed more than 8000 sea-ice maps derived from SSM/I passive microwave satellite data (Fowler et al., 2000). We divided the Greenland Sea into 4 main regions based on direction from ZRA, and each of them was further divided into 5 sub-regions based on distance from ZRA (Fig. 2). For each season (December-August), and each of the 20 regions, the time-duration (number of days with sea-ice percentage above a certain threshold) was calculated and compared to the end-of-winter snow accumulation at ZRA. To validate our results we calculated correlation-coefficients between snow accumulation and sea-ice extent using end-of-winter snow accumulations calculated from both of the above mentioned approaches. The correlation between sea-ice extent within the Greenland Sea and snow accumulation around ZRA is visualized spatially in Fig. 2. All of the regions show an inverse relationship between extensive sea-ice duration and snow accumulation (the more sea-ice the lesser the snow accumulation and vice versa), and the further one goes to the south and southeast the higher the correlation. This pattern seems to be evident (see the tables in Fig. 2) no matter which of the snow modeling approaches applied. The highest correlation occurs in the SSE region when ice-data up till a distance of 750 km from ZRA are included. This leads us to the conclusion that a “center of action”, which highly influences winter-precipitation amounts in Northeast Greenland is centered within this region – around 500 km north of Iceland between Greenland and the Island of Jan Mayen.



R² – Coefficients regional (19 years)

	NNE	NE	SE	SSE
100 km	(0.21)	0.22	0.18	0.19
250 km	(0.19)	0.35	0.47	0.39
500 km	(0.50)	0.24	0.43	0.46
750 km	(0.56)	0.25	0.43	0.50
1000 km	(0.57)	0.25	0.43	0.51

R² > 1% sig. lev. (0.28 for 19 obs.)

R² – Coefficients Zackenberg (12 years)

	NNE	NE	SE	SSE
100 km	(0.20)	0.19	0.19	0.23
250 km	(0.20)	0.35	0.49	0.54
500 km	(0.41)	0.51	0.62	0.61
750 km	(0.42)	0.47	0.63	0.65
1000 km	(0.49)	0.52	0.64	0.66

R² > 1% sig. lev. (0.43 for 12 obs.)

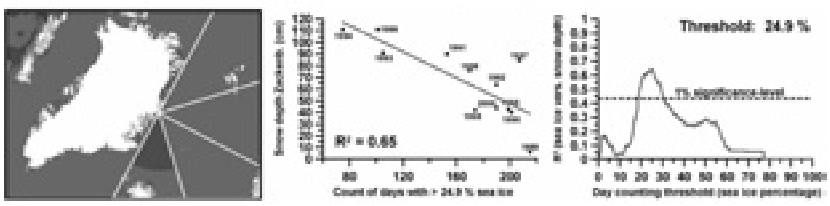


Fig. 2. Spatial distribution of the correlation between (1) end-of-winter- snow-precipitation amount in the Zackenberg Region (21,000 km^2 – regional scale) and (2) the number of days during December to August with sea-ice percentage above a critical threshold (which differs from sub-sector to sub-sector). The Greenland Sea is divided into four sectors based on direction seen from Zackenberg Research Station (ZRA): NNE, NE, SE, SSE, and each sector is further divided into five sub-sectors based on distance from ZRA: 0-100 km, 0-250 km, 0-500 km, 0-750 km, and 0-1000 km (note that a smaller sub-sector is always included in a larger sub-sector). The tables display R^2 coefficients of a least squares fit between end-of-winter snow-precipitation amount (at regional and local scales, respectively) and duration of periods with extensive sea-ice. At the bottom, the sub-region (750 km SSE) that gives the highest correlation between snow-precipitation and time-duration of extensive sea-ice is shown. The linear fit in the middle is based on local scale snow modeling over 12 years, and the diagram to the right shows that in this case a threshold of 24.9% (number of days during December-August with more than 24.9% sea-ice cover), gives the optimum correlation for the region in question (here SSE 750 km sub-sector).

3. Discussion/perspectives

With the prospect of decreasing sea-ice off Northeast Greenland in the future, this study shows that more snow-precipitation can be expected on land. Since limited snow cover and large snow free areas today is an important precondition for the High Arctic "desert" of North and Northeast Greenland, increased snow cover in combination with increased frequency of thaw events will alter the conditions in the direction of present-day Low Arctic Southeast Greenland. For flora and fauna this would mean increased vegetation cover on presently barren lowlands, but also difficulties for herbivores from lemmings to musk oxen due to melting snow and rain in winter resulting in ice crust formation. If summer temperatures, as predicted, do not increase noteworthy, the heavier snow pack may delay spring snow clearance in High Arctic Greenland, as opposite to the predicted prolongation of the growing season in most of the Arctic. This will delay the reproductive phenology and thereby the success of many species ranging from plants to shorebirds (Meltofte 2002). If on the contrary, summer temperatures do increase significantly, the High Arctic tundra and desert may transform into Low Arctic tundra, leaving the High Arctic habitat only as an alpine zone in mountainous areas (Meltofte et al. 2003).

At the time of writing there are still questions that need to be clarified. Thus, more research has to be done in order to explain what mechanisms actually affect the sea-ice distribution within the regions of high correlation. Teleconnection patterns such as the Arctic and North Atlantic Oscillations (AO and NAO) do not seem to explain ice cover variations in these regions very well, and neither does modeled sea-ice fluxes through the Fram Strait (Schmith and Hansen, 2003). However, as the sea-ice distribution in the Greenland Sea is influenced by both local ice formation and a large ice-flux from the Arctic Ocean into the East Greenland Current, it cannot be generalized at a larger scale. Therefore, it might be that sea-ice formation and distribution in the southern Greenland Sea should be addressed to other (more local) factors such as the so called Odden ice tongue phenomenon (Wadhams, 1999) and/or atmosphere-ocean interactions. In this connection e.g. the position of the ice edge plays a crucial role in the formation of polar lows (Rasmussen et al., 1992).

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Climate Records from Temperate Ice Caps in Iceland: Pilot Studies on Hofsjökull

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Introduction

Covering an area of 880 km^2, Hofsjökull is the third largest ice cap in Iceland. Outlet glaciers flow in all directions from the main ice cap, which is almost circular in shape (Fig. 1). The surface and bedrock topography of Hofsjökull was mapped in 1983 [1], revealing the presence of a subglacial mountain massif of volcanic origin under the central part of the ice cap. The average thickness of Hofsjökull is 215 m, but the ice thickness reaches a maximum of 750 m in the center of an ice-filled volcanic caldera, ~40 km^2 in area, situated west of the summit of the ice cap, which is at 1790 m above sea level.

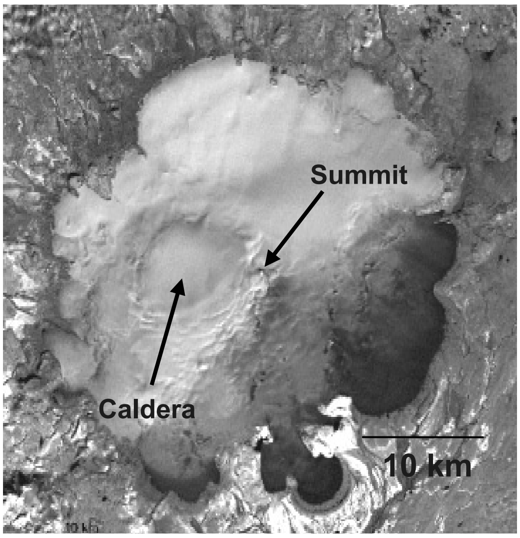

Fig. 1 – Hofsjökull ice cap, Central Iceland

Monitoring mass balance and ice margin positions

The annual mass-balance of Hofsjökull has been measured continuously since 1988 [2,3]. Net balance at the summit site (measured over the 12 month period Sept. 1 to Aug. 31) has varied between 531 cm water equivalent in 1991/1992 and 239 cm w.eq. in 1996/1997. Average net balance in the period 1987/2003 was 340 cm. The net balance on the ice cap as a whole was positive in 1988/89 and in the period 1991 to 1994. In other years it was negative. On average, the ice cap has thinned by about 3-4 m (w.eq.) during the 17 years of mass-balance measurements. All outlet glaciers from Hofsjökull have been receding since 1995 and the total area of the ice cap has shrunk by approximately 3.5 % since 1986.

Ice core study: Identifying annual layers in temperate ice

Accurately dated ice-core records provide a means of prolonging mass-balance data sets further back in time. All ice caps in Iceland are temperate (i.e. at melting point throughout) and summer melt is known to affect the seasonal variation in several parameters commonly used for dating polar ice cores. In spite of these problems, temperate ice caps around the world are now receiving increased attention as potential archives of past environmental changes [4,5]. At high-elevation sites in Iceland (above 1700 m a.s.l.), summer melting is negligible and pilot studies have shown conclusively that windblown dust of local origin, deposited on the top of Hofsjökull during the summer, produces well-defined horizons that can be used for annual layer counting in ice cores [4,6]. A total of 33 annual layers could be identified in a 100 m ice core drilled at the Hofsjökull summit in 2001 [3,4,7]. The thickness of each annual layer was converted into ice-equivalent thicknesses and a model describing the plastic thinning of annual layers with depth [8] was then used to calculate the original thickness of the layers at the surface, providing information on the net annual balance in the period covered by the ice core.

Precipitation and temperature proxy records from the Hofsjökull core

Fig. 2 shows the calculated annual balance for the period 1971-2000. The 1988-2000 yearly mass-balance record is shown for comparison, revealing an excellent match between the two records. The data set reveals considerable variability in annual precipitation on Hofsjökull in the above mentioned period, but a definite trend is not observed. Precipitation at the nearby weather station Hveravellir, located 35 km west of the drilling site, 650 m a.s.l., is shown for comparison. As indicated by the scatterplot in Fig. 4, the two records match each other reasonably well. A sharp drop in precipitation from the 1975-76 glacier year to the 1976-77 year is seen in both records, and the 1988-89 and 1991-92 peaks are prominent in each of the three records.

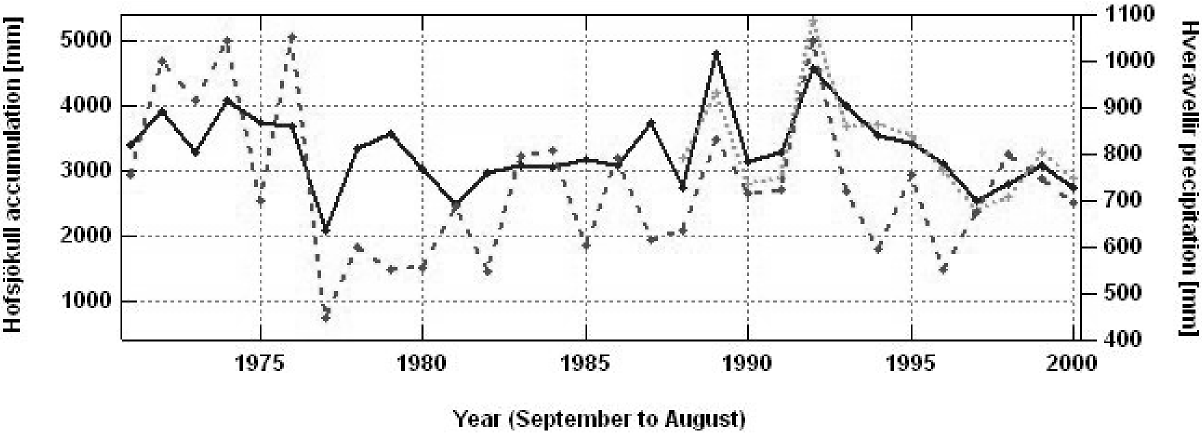

Fig. 2 – Full curve: Net accumulation from ice core, Hofsjökull summit. Glacier years 1970-71 to 1999-2000. Dotted curve: Net accumulation at Hofsjökull summit from yearly mass balance measurements on site. Dashed curve: Annual precipitation at Hveravellir (from September to August, to facilitate comparison with the ice core data) – vertical axis on the right.

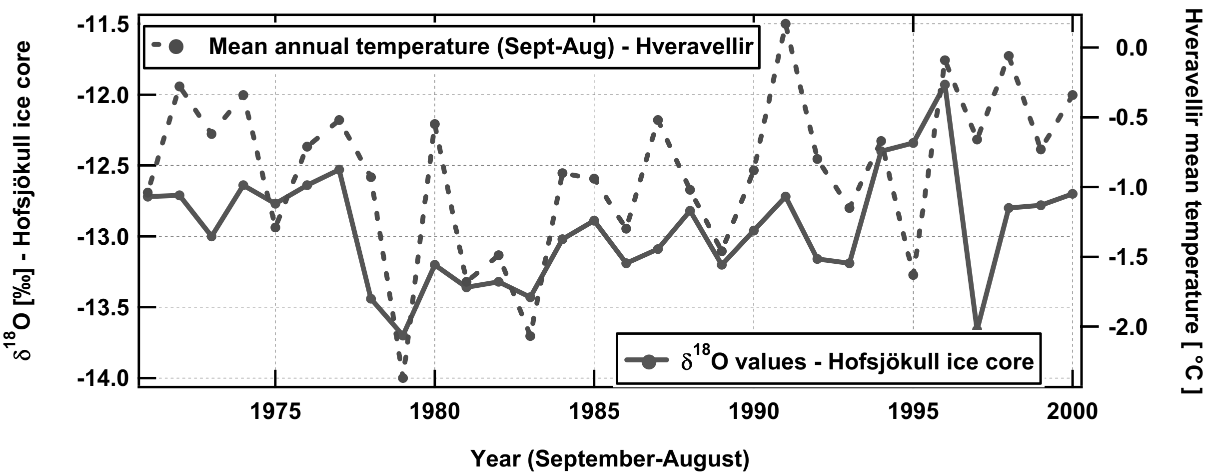

Fig. 3 – Full curve: $\delta^{18}O$ values from the Hofsjökull core (averages for each annual layer, 20 cm samples) Dashed curve: Mean annual temperature (Sept-Aug) at Hveravellir, 1970-71 to 1999-2000.

Measurements of oxygen-isotope ($^{18}O/^{16}O$) ratios on the core yield $\delta^{18}O$-values varying between -8.7 ‰ and -17.2 ‰, with an average of -12.9 ‰. Seasonal variation is observed in the highest 5 annual layers, but homogenization occurs below 20 m depth, although a weak seasonal signal with an amplitude of 0.2-0.5 ‰ appears to be present down to 100 m [4]. Mean $\delta^{18}O$-values for each annual layer in the core are shown in Fig. 3, along with (Sept-Aug) mean annual temperatures at Hveravellir. A correlation is evident from these data and the linear fit in Fig. 5 yields the δ-T relationship: $\delta^{18}O = 0.34*T - 12.63$ ‰; i.e. a δ-T slope of 0.34 ‰/°C. In comparison, the present-day δ-T slope obtained in the central part of the Greenland ice sheet is 0.67 ‰/°C [9].

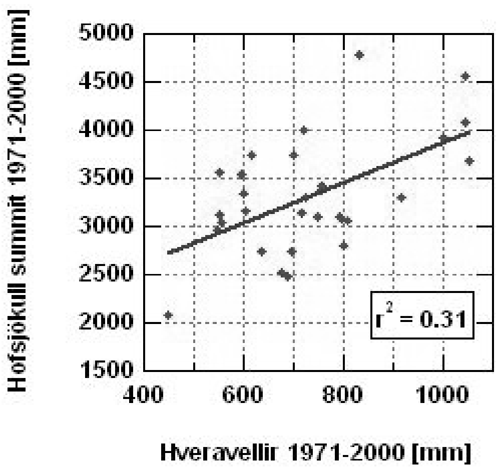

Fig. 4 – Hofsjökull net accumulation vs. Hveravellir precipitation 1971-2000.

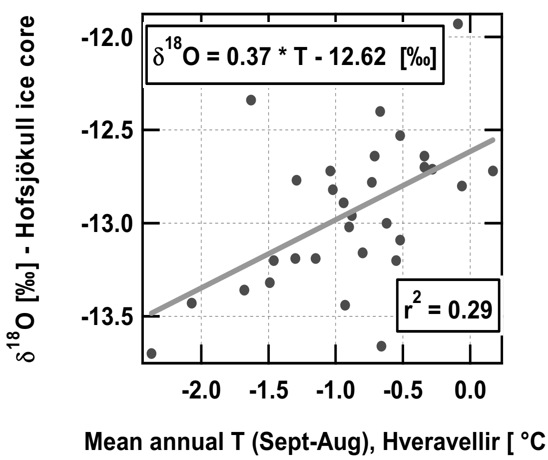

Fig. 5 - $\delta^{18}O$ in the Hofsjökull core vs. mean annual temperature at Hveravellir 1971-2000

Future work

Studies of the 100 m core from Hofsjökull have shown that ice cores drilled at high elevations on the temperate ice caps in Iceland can be accurately dated and can yield valuable information on past variations in climate parameters. A core drill designed for operation in temperate ice is now being built in Iceland and reconnaissance studies in preparation for deeper drillings are ongoing [6]. Model calculations indicate that 500 years old ice could be retrieved at the Hofsjökull summit, where the ice thickness is 300 m, and up to 1000 years old ice could be present near the bed in the central part of the summit caldera, where the ice thickness reaches 750 m. Future ice core drillings on Hofsjökull could thus likely provide climate records for the North Atlantic region reaching through the Little Ice Age and into the Medieval Warm Period. In addition, the calibration of ice core records against instrumental records covering the past 150 years will greatly aid current efforts to calculate the impact of future climate change on glaciers in Iceland and elsewhere [10].

Acknowledgements

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Thermokarst Development in a Changing Climate

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Climatic warming is particularly evident in areas underlain by relatively warm, ice-rich permafrost in Subarctic and Arctic Alaska. Thermokarst topography forms whenever ice-rich permafrost thaws, either naturally or anthropogenically, and the ground surface subsides into the resulting voids (Figure 1). The important and dynamic processes involved in thermokarsting include thaw, ponding, drainage, surface subsidence and related erosion. These processes are capable of rapid and extensive modification of the landscape; preventing or controlling anthropogenic thermokarst is a major challenge for northern development. We will present an investigation of the physical factors that influence thermokarst formation and discuss the implications of this process on local ecology, hydrology and surface energy balance.

The active layer is that portion of the soil above permafrost that annually experiences thawing and freezing. The depth to which the active layer thaws each summer depends upon many interacting factors, especially site hydrology. Other seasonal factors that influence depth of thaw include air temperature and soil moisture, which in turn varies in response to precipitation and evapotranspiration. The inter-annual variation of thaw depth at a site is large. Consequently, utilizing depth of thaw as an indicator of climatic change may be difficult as the climate change response will likely be subtle amidst large annual variations. Nevertheless, the deeper permafrost acts an integrator of meteorological variations and will respond to long-term changes in climate. It must also be recognized that changing the surface configuration and condition will also impact deeper ground temperatures and thus may mask (or overwhelm) changes in temperature due to changing climate.

Thermokarsts play an important role in response to a warming climate by altering hydrological flowpaths. Thermokarst may form in continuous or discontinuous permafrost, as controlled by the surface energy balance, soil thermal and hydraulic properties, and snow cover. Permafrost is generally continuous above the Arctic Circle in North America and Eastern Russia, but discontinuous permafrost does extend as far south as 50ºN latitude over Canada and Russia (Brown et al., 1998). Alpine permafrost exists in high mountainous regions throughout the world, even in the tropical latitudes. In the far northern regions of Alaska and Russia, permafrost may penetrate as deep as 600 to 800 m. Even within these bounds, small areas of unfrozen ground called taliks exist beneath large lakes and rivers or near springs (Permafrost Subcommittee 1988). Typically in areas of thick, relatively impermeable permafrost, the surface water is effectively isolated from sub-permafrost groundwater processes. However, in some isolated locations, springs extend through the permafrost to release groundwater at the surface. Groundwater springs may penetrate thick permafrost; the limiting factors of permafrost thickness and ground temperature must be offset by spring flow rate and water temperature. Subsurface hydrologic flowpaths are strongly coupled to thermokarst and talik formation in permafrost regions. In zones of thinner permafrost (tens to hundreds of meters) taliks may extend completely through permafrost allowing groundwater recharge or discharge. These taliks allow connection of deeper sub-permafrost groundwater with surficial water bodies. In some cases (depending upon the thickness of the permafrost), taliks allow ground water recharge as the water from rivers and lakes infiltrates to the sub-permafrost aquifer (Yoshikawa and Hinzman, 2003) or in reverse as groundwater discharge (Jorgenson et al., 2001) as typically occurs in wetlands.

Thermokarst is especially responsive to climatic change and several have been observed in Interior Alaska in recent years. Some of these thermokarsts have been linked to distinct events such as wildfire, floods or road construction, but some appear with no apparent cause for initiation other than perhaps a warming climate. Such thermokarsts may be the first indicator of substantial geomorphological and ecological change. As thermokarsts form, drainage is actually improved in the area immediately adjacent to the pond. Occasionally sloughing of banks enhances thawing and erosion, while exposing buried organics. These processes impact aquatic systems through stream chemistry and sedimentation. Increased thermokarst can result in greater interactions with disturbed organic soils and deeper groundwater systems, yielding greater transport of cations, and dissolved and particulate organic carbon. They also create favorable conditions for establishment of spruce trees and various shrubs (Lloyd et al., 2003). Slightly drier soils along thermokarst banks promote introduction of woody species as compared to adjacent tundra. Such processes may accompany northward expansion of treeline.

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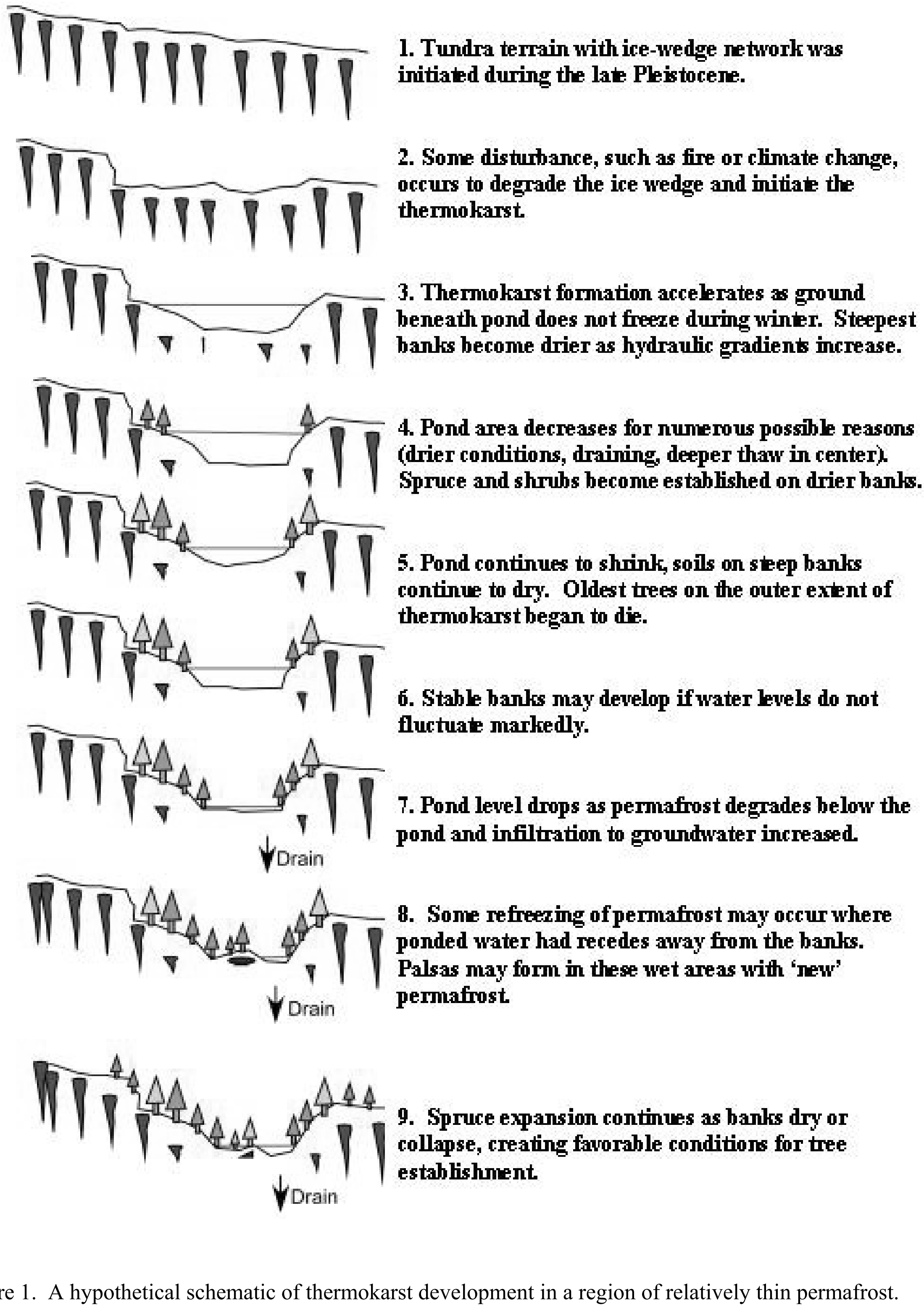

Figure 1. A hypothetical schematic of thermokarst development in a region of relatively thin permafrost. Vertical drainage below the thermokarst is only likely to occur in subarctic regions where permafrost is usually less than 50 m thick and is often discontinuous (occurring primarily on north-facing slopes and valley bottoms). In such conditions, the groundwater gradient could also be reversed and groundwater could flow upwards to recharge the pond (Kane and Slaughter, 1973).

A Climatic Perspective on Observed Arctic Permafrost Changes

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Introduction

Changes in the Arctic atmosphere-ice-ocean system observed in recent years are the background for frequent discussions as to whether these changes represent episodic events or long-term shifts in the Arctic environment. Existing knowledge on Quaternary climate and Global Climate Models (GCMs) predict that the effect of any ongoing and future global climatic change should be amplified in the polar regions due to feedbacks in which variations in the extent of glaciers, snow, sea ice and permafrost as well as atmospheric greenhouse gases play key roles. GCM analyses suggest that the Polar Regions should by now be experiencing a much larger warming than registered at lower latitudes, and sub-continental scale analysis of meteorological data obtained during the observational period apparently lends empirical support to the alleged high climatic sensitivity of the Arctic (Giorgi, 2002). Polyakov et al. (2002), however, questions the concept of polar amplification of temperature changes observed by surface stations at lower latitudes.

There is reason therefore to evaluate recent climate dynamics and their respective impacts on high-latitude ecosystems, including permafrost regions. Permafrost presently occupies about 25% of the Northern Hemisphere land surface (Brown et al., 1997). Permafrost thereby is a significant characteristic in many natural environments, especially in the Northern Hemisphere, affecting hydrology, geomorphic processes and slope stability, although first recently recognized as a potential geohazard factor. Variations in permafrost temperatures and -distribution may have direct consequences for timing and distribution of rock slides and mudflows, safety, building stability and socio-economy.

A persistent research question within permafrost science has been the precise nature of the relation between mean annual air temperature (MAAT), the mean annual ground surface temperature (MAGST), and the temperature at the top of permafrost (TTOP). Conventionally, the extent of permafrost has been represented in terms of the regional-scale pattern of air temperature isotherms, although the relation between climate and permafrost has not been explicitly defined. There is reason therefore to consider permafrost regions in the Northern Hemisphere in an overall Arctic meteorological-climatic context.

Modern Arctic climate

Modern climate in the Arctic is to a high degree regulated by the advection of warm North Atlantic waters into the Nordic Seas near Svalbard, the Norwegian- and the Greenland Sea. Maritime climate conditions prevail over much of the Arctic Ocean, coastal Alaska, Iceland, northern Norway and adjoining parts of Russia. In these areas, winters are generally cold and windy. Summers are cloudy and cool with mean temperatures ranging from 4 to 8^{o}C over land areas. Annual precipitation ranges from 400 mm to 1300 mm (w.e.), with a cool season maximum (largely snowfall) and about five to seven months of continuous snow cover. Shallow permafrost (0-250 m) characterise these regions. Forests are absent or found only close to sea level in sheltered positions due to low summer temperatures and windy conditions.

Arctic interior continental climates have more severe winters and precipitation is usually small. The coldest part of the Northern Hemisphere is located in northeast Siberia near the city Verkhoyansk, where present mean winter (DJF) air temperature is around –43°C. Although frost may occur in any month, long summer days usually provide up to three months with mean air temperatures above 10°C, and at some sites in the continental interiors summer temperatures may even exceed 30°C. In such regions, forests extend 200-1000 km north of the southern limit of permafrost and, consequently, permafrost extends far beyond the traditional warm limit of periglacial environments (the tree line). Permafrost is widespread and typically reaches 300-600 m in thickness. Permafrost thicknesses in excess of 1000 m are likely in some areas of northern Siberia, and such permafrost may potentially be of very high age.

The Siberian High is an intense, cold anticyclone that forms over eastern and southern Siberia in winter. Strong cooling in this region results in the lowest air temperatures in the Northern Hemisphere. The Siberian High forms usually in October, mainly in response to strong and continuous radiational cooling in the lower troposphere above the snow-covered surface of Asia, and persists until around the end of April. Being primarily thermally induced, the Siberian High is a shallow cold-core system mainly confined to the lower levels of the troposphere below the 500 hPa pressure level. Another persistent anticyclone or high-pressure ridge called the Arctic High, also known as the Beaufort High, is located over the Beaufort Sea and the Canadian Archipelago in winter and spring. The Arctic High is a relatively weak area of high pressure that covers most of North America during winter, and extends across the Arctic Ocean towards the Siberian High. The interaction between the Arctic High and the Icelandic Low causes frequent outbreaks of cold air masses over eastern Canada and into the North Atlantic east of Greenland. These outbreaks of cold air are the drivers for deep water formation in the Labrador Sea and in the Greenland Sea, background for the thermohaline circulation.

Arctic climate and permafrost

The extensive permafrost areas in Mongolia and in central and eastern Siberia are under the direct influence of the Siberian High and experience extremely cold and dry conditions associated with minimal cloud cover and substantial longwave radiation losses to the atmosphere. Despite its prominence and large spatial extent surprisingly little is known about the temporal variability of the Siberian High and its possible impacts on meteorology, climate and permafrost in the Northern hemisphere.

Siberian extensive permafrost regions spatially fit with the typical winter extension of the Siberian High, suggesting this to be a permanent Holocene weather feature. Also the frequent cold air outbreaks over East Asia from the Siberian High are likely to be of importance for the modern distribution of permafrost in Asia. In Europe, the advection of warm Atlantic air masses is controlled by the interaction of the Siberian High and the Icelandic Low. This large-scale circulation feature limits modern permafrost in Europe to high latitudes near the Arctic Ocean or to high altitudes. In North America, extensive lowland permafrost in Alaska and western Canada is associated with the typical winter position of the Arctic High. Low altitude permafrost is mainly absent in southeast Alaska due to warm Pacific air masses advected by the Aleutian Low. In eastern Canada, discontinuous and sporadic permafrost extends to about 50°N south of Hudson Bay and in Labrador. This sector is strongly influenced by outbreaks of cold air masses from the Arctic Ocean between the Arctic High and the Icelandic Low.

The major Arctic permafrost regions found in Siberia, Canada and Alaska are thus all associated with the typical position of major anticyclones such as the Siberian High and the Arctic High, emphasising the notion of permafrost ultimately being a climatic phenomenon.

Modern Arctic climate variability and permafrost

Projections of future climate changes in the Arctic are complicated by possible interactions involving surface changes, oceanography, stratospheric temperature, stratospheric ozone, and other changes. Thus, current model estimates of future changes in the Arctic disagree as to both the magnitude of changes and the regional aspects of these changes. Moreover, causes of soil temperature changes in the upper few meters in permafrost regions are still not well documented, and one major obstacle to understanding the linkage between the soil thermal regime and climatic change is the lack of long-term observations of soil temperatures and related meteorological variables. The present paper therefore investigates temporal and spatial surface air temperature changes within the entire Arctic, using meteorological data up to December 2002, in order to improve understanding of observed permafrost and active layer changes.

The period 1915-1940 represents the well known early 20th century warming in the Arctic, especially influencing northern Alaska, northern Canada, Greenland and the northern parts of Russia and Siberia. The following period 1940-1965 represents a period of widespread cooling in the Arctic. Temperature changes were most pronounced during the winter and weaker expressed in other seasons. Especially Alaska, northwestern Canada, Svalbard, the Kara Sea and eastern Siberia were affected by this development. The final 35 years of the 20th century (1965-2000) has been a period of renewed warming in many parts of the Arctic. Again this development has been most pronounced in the winter season and less so in other seasons. The late 20th century Arctic warming has affected especially western Canada, Alaska, eastern Siberia and a region east of Svalbard. In western Siberia and eastern Russia the air temperature changes have been limited. Eastern Canada, western Greenland and the northern Pacific have been exposed to a slight net cooling.

The climatic development during the final 10 years of the 20th century (1990-2000), however, deviates from the longer 1965-2000 period. Temperatures are now decreasing in Russia and Siberia, and warming is confined to the Atlantic sector of the Arctic Ocean, West Greenland, Canada and northernmost Alaska. Especially the Hudson Bay region, central West Greenland and Svalbard are affected by this recent warming. The air temperature changes 1990-2000 are highest during the winter and smallest during summer. The autumn season also stands out, with marked warming affecting most of the Arctic Ocean and NW Canada, suggesting increased cyclonic activity and later onset of winter. On the other hand, spring is delayed in parts of Russia, Siberia, eastern Alaska and western Canada. These different late 20th century climatic developments at least partly explain conflicting reports on ongoing permafrost change in different Arctic regions

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Response of Glaciers in Iceland to Climate Change

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Introduction

Global warming due to increasing concentrations of CO_2 and other trace gases in the atmosphere is expected to have pronounced effect on glaciers and lead to major runoff changes from glaciated areas. The research projects *Climate, Water and Energy* (CWE, http://www-.os.is/cwe) and *Climate and Energy* (CE, http://www.os.is/ce) and their Icelandic counterpart *Veðurfar, vatn og orka* (VVO, http://www.os.is/vvo) aim to estimate the effect of global warming in the Nordic countries on renewable energy resources, in particular hydrological effects with possible consequences for the operation and planning of hydroelectric power plants.

Mass balance data from glaciers and ice caps contain implicit information about the dependence of glacier mass balance on climate. The meteorological conditions on typical glaciers and ice caps span a large range of temperature and precipitation due to the large altitude range, which is often on the order of 1000 m. As a consequence, climate conditions in the near future are likely to remain within the already observable range on the glaciers to some approximation, unless the climate changes are so large or rapid that the climate of the region changes in a fundamental way. Thus, parameter values, determined from mass balance observations for the current climate, may be expected to be meaningful for climate change studies.

Melting of all existing glaciers and ice caps, excluding the large ice sheets of Greenland and Antarctica, would raise global sea level by about 0.5 m. Although glaciers and ice caps in Scandinavia and Iceland constitute only a small part of the total volume of ice stored in glaciers and small ice caps globally, studies of their sensitivity to climate changes have a general significance because these glaciers are among the best monitored glaciers in the world. Field data from glaciated regions in the world are scarce due to their remote locations and difficult and expensive logistics associated with glaciological field work. Results of monitoring and research of Nordic glaciers are therefore valuable within the global context, in addition to their importance for evaluating local hydrological consequences of changes in glaciated areas in these countries.

Glacier mass balance depends on the amount of snowfall during the accumulation season and on the melting or ablation of snow and glacier ice during the ablation season. Glacier mass balance observations are sensitive indicators of climate change and they also have several advantages for use in precipitation studies. They are typically from areas where there are few other precipitation measurements, but where precipitation estimates are important for many applications. Precipitation estimates based on mass balance measurements in glaciated areas are also not affected by the undercatch of traditional precipitation gauges, and they may provide a dense spatial coverage with a limited measurement effort because the measurements are only carried out a few times a year. Glacier mass balance measurements are an important component in the monitoring of climate change in Arctic and sub-Arctic areas.

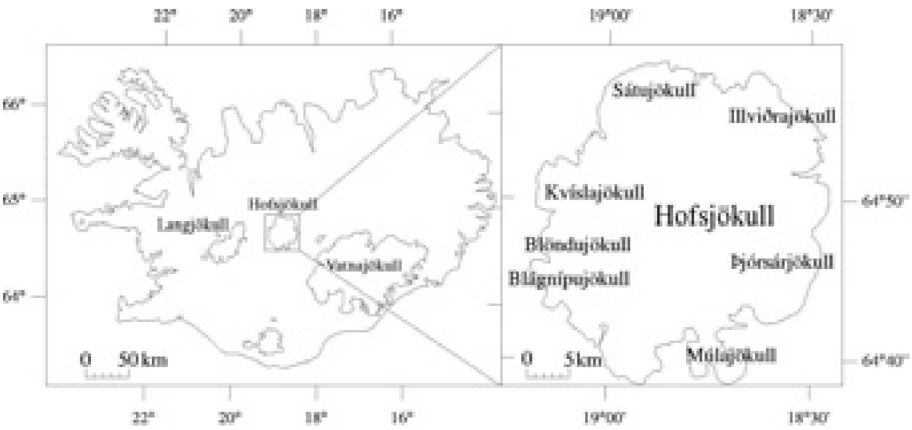

Figure 1. Location map.

This paper summarises some the results obtained by the Glaciers work groups of the CWE, CE and VVO projects for glaciers in Iceland. More detailed descriptions of the results of the projects are described by Jóhannesson *et al.* (2004) and Aðalgeirsdóttir *et al.* (2004) and may be obtained from the web-sites of the projects that are given above.

Climate Change Scenario

The climate scenario for the CWE project is described by Räisänen (2003). It provides a projection of climate change in the Nordic countries for the period from 1990 to 2050. In Iceland it prescribes an approximately sinusoidal temperature variation with a maximum of +0.3°C per decade in winter and a minimum of +0.15°C per decade in summer. The precipitation change in the glacier simulations was specified with a constant relative change of 5% per degree of warming independent of season. In addition, a climate change scenario from a previous climate change project, *Climate Change and Energy Production* (CCEP), was also used in the glacier modelling (Jóhannesson *et al.*, 1995). This scenario prescribes a yearly mean warming of 0.3°C per decade, varying from a winter maximum of +0.35°C per decade to a summer minimum of +0.25°C per decade, and a relative precipitation change of 5% per degree of warming independent of the season as in the CWE scenario. This warming is closer to the projected warming in other ocean areas on a similar latitude as Iceland, although not as high as in Scandinavia or other continental areas in this latitude range. The use of the climate change scenario from the previous CCEP study serves the purpose to investigate the consequences of climate change in case the strength of the thermohaline circulation in the North Atlantic Ocean is not reduced as much as projected by some coupled OAGCMs.

Results of Glacier Modelling

Degree-day mass balance models and 2D finite difference dynamic models were calibrated for the Hofsjökull ice cap, central Iceland, and for the southern part of the Vatnajökull ice cap, south-eastern Iceland (Figure 1). In these models, glacier accumulation and ablation are computed from daily temperature and precipitation observations at nearby meteorological stations and depth-averaged ice flow is computed from local ice thickness and surface slope. Figure 2 shows the projected reduction in ice volume corresponding to the climate scenarios described above. The volume of ice is in both cases reduced almost by half (little less relatively for Hofsjökull) within 100 years and the ice caps have almost disappeared 200 years after the start of the simulations. The northern and western flanks of Vatnajökull are

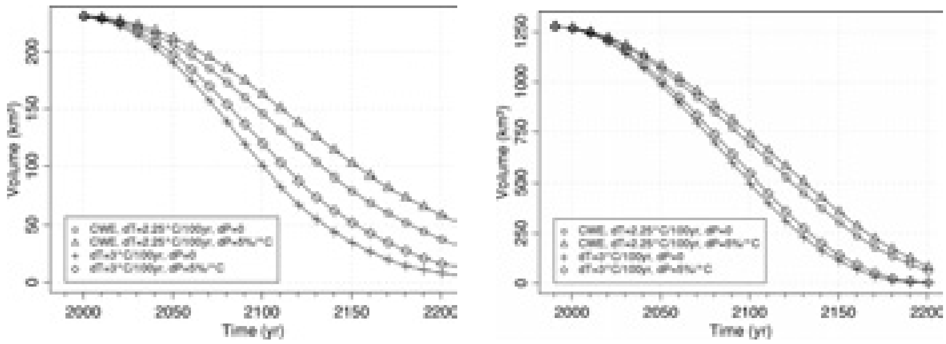

Figure 2. Projected volume of the Hofsjökull ice cap (*left*) and the southern part of the Vatnajökull ice cap (*right*) according to four climate scenarios.

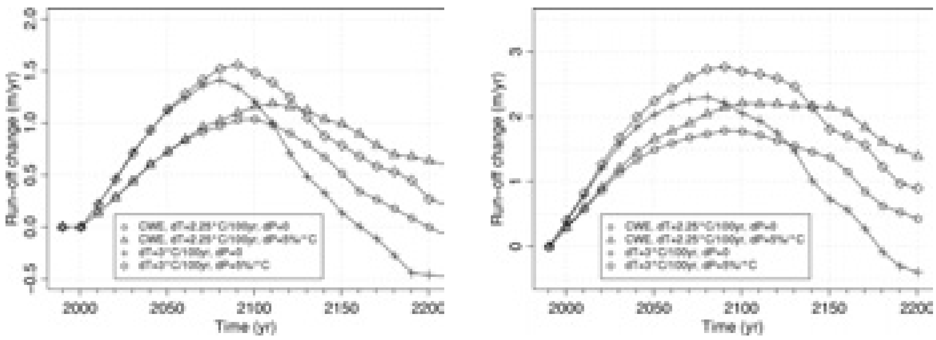

Figure 3. Projected runoff increase from the area initially covered by the Hofsjökull ice cap (*left*) and the southern part of the Vatnajökull ice cap (*right*) according to four scenarios.

excluded from the dynamic computations due to surges in these parts of the ice cap which are not adequately described by the dynamic model.

The reduction in the volume of the ice caps leads to a substantial increase in glacier runoff as shown in Figure 3. At about 2030, the runoff change is in the range 0.5–0.8 ma^{-1} for Hofsjökull and 1.1–1.7 ma^{-1} for the southern part of Vatnajökull, which is approximately 30% of the current average runoff from the ice caps. The projected runoff change increases approximately linearly to a maximum of 1–1.5 ma^{-1} for Hofsjökull and 1.75–2.75 ma^{-1} for the southern part of Vatnajökul in about 2100 after which it levels off and decreases due to the decreasing area of the ice caps.

Conclusions

Changes in glacier runoff are one of the most important consequences of future climate changes in Iceland, Greenland and some glaciated watersheds in Scandinavia, with important implications for the hydropower industry. Rapid retreat of glaciers also has other implications, for example changes in fluvial erosion from currently glaciated areas, changes in the courses of glacier rivers, which may affect roads and other communication lines, and changes that affect travellers in highland areas and the tourist industry. In addition, glacier changes are of international interest due to the contribution of glaciers and small ice caps to rising sea level.

Acknowledgements

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Establishment of Decadal-scale UV Climatologies for High-latitude Ecosystems Studies

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Introduction

Solar ultra-violet radiation (UVR) is an important natural geophysical parameter influencing terrestrial and aquatic eco-systems all over the globe *(Häder, 1997)*. In the Arctic, UVR, though on an average being much weaker than at low latitudes, can be an important stress factor mainly due to high surface reflectance from snow and ice, very high transparency of water and extended daylight at the beginning of the biologically productive period. This role can be further reinforced under special conditions such as polar ozone depletion occurring during spring. A comprehensive documentation of UV and its effects on ecosystems in the Arctic is given in *Hessen (2002).*

To understand eco-system responses to UVR changes, both process studies and long-term correlation studies using realistic input data are necessary. However, in-situ UVR measurements with sufficient accuracy and adequate quality assessment and control only have existed for about a decade. In order to establish UV series for a longer time scale, one has to combine measurements of the most important parameters influencing UVR with radiation transfer models, which have experienced a considerable improvement in recent years, both due to the development in methodology and increasing computing capacity. These goals were addressed in two subsequent international projects, MAUVE and UVAC. The first project had its focus on development and testing methods to derive UVR from satellite measurements, while UVAC addressed a concrete application in the high-latitude marine environment. In the following we give a short description of the UV climatologies for the Lofoten region, North-Norway, derived from two independent methods based on satellite data and one based on ground-based measurements and the application in the frame of the UVAC project.

Methods

Apart from the “fixed” parameters solar elevation/geographical latitude and surface elevation (topography), the most important parameters influencing UV radiation levels at the surface are: total ozone, cloud coverage and thickness, surface albedo and atmospheric aerosol optical thickness. The method developed at JRC uses METEOSAT cloud data, which have been available since 1984. The geostationary orbit of this instrument implies a less favourable geometry at high latitudes causing a decrease of spatial resolution to some tens of km. On the other hand, it provides approximately half-hourly cloud scenes allowing, in principle, to follow variations in cloud cover throughout the day. The method developed at DLR uses cloud data from the AVHRR instrument which also is available since the mid-1980s and which has a polar orbit. These give a much better spatial resolution of about 1x1 km, but usually have only one overpass per day over a site. Both methods use total ozone data from the TOMS instrument, which has been available since 1979, complemented with other data sets, such as GOME and TOVS, in data gaps especially in the mid-1990s. Also with respect to other parameters the two methods differ: The JRC method includes a topography model, and visibility data to estimate the aerosol content of the air, while the DLR model uses an aerosol climatology and no topography, thus mainly being usable for marine applications. A detailed description of the two methods is given in *Verdebout (2000)* and *Meerkötter and Bugliaro (2002).* A systematic comparison of the two resulting datasets has yielded a remarkably good agreement *(Meerkötter et al., 2003).*

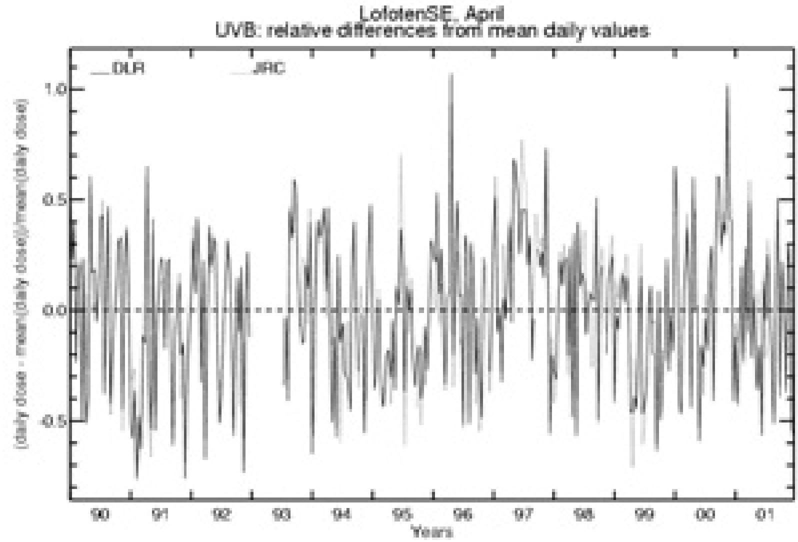

Figure 1. Relative deviations of the satellite derived surface UV-B radiation (DLR and JRC method) to the mean value for April in the period from 1990 to 2001.

Figure 1 shows daily UV doses in April throughout the years 1990-2001 as derived with both satellite-based methods. Obviously, the general agreement is very good on most days in April, but the DLR method shows more pronounced extreme values, which is not unexpected due to the higher spatial resolution. The figure also shows an increased number of days with higher-than-average daily doses in 1997 and 2000, two years with severe ozone depletion and high albedo due to large amounts of snow.

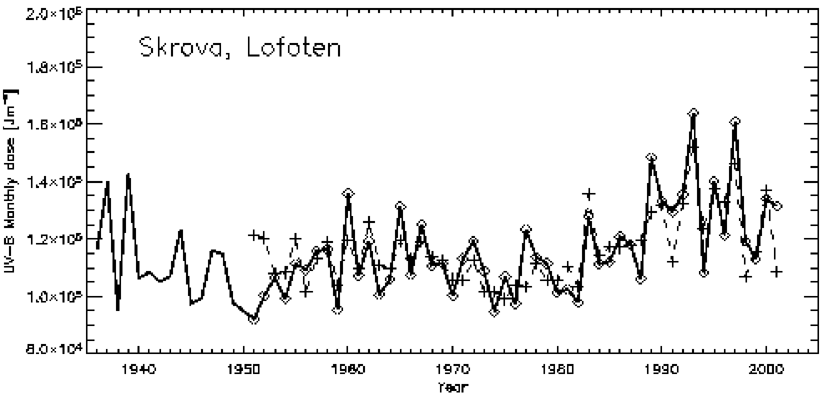

Figure 2. Monthly UV-B dose in April at Skrova, Lofoten, calculated from Tromsø total ozone and local meteorological cloud observations. Dashed line: fit derived using a multi-linear regression model (Hansen et al., 2004).

A third climatology, which covers a much longer time period, but is limited to one geographical location, was established at NILU. It is based on the 68-year records (1935-2003) of total ozone in Northern Fennoscandia (Tromsø, complemented with data from Murmansk, Sodankylä, and Andøya) and cloud coverage (visual observations) at Skrova, Lofoten. The cloud information in this method is very crude (cloud fraction in octals, i.e. a value between 0 and 8), but comparison with UV measurements has shown that aggregated UV data, such as weekly and monthly means as well as maximum daily doses agree quite well *(Engelsen et al., 2004).* The April monthly doses of this series are depicted in Figure 2. They show an overall increase especially since the 1970s, but also significant decadal-scale variations with intermediate maxima at the end of the 1930s, around 1960 and in the 1990s. As pointed out in *Hansen et al. (2004)*, this variation is mainly due to variations in cloud coverage, while the UV increase since the 1970s is mostly due to the depletion of the stratospheric ozone layer.

Applications

When applying such climatologies in ecosystem studies, the crucial question is in which way the geophysical parameter influences biological systems. Concretely spoken for this case: Are aquatic ecosystems mostly influenced by short-time maximum UVR doses or integrated doses, say over a week or even a month, and at which time of the year or of biological cycle?

In the frame of the UVAC project, a number of geophysical parameters (NAO index, AO index, Gulf Stream Index (GSI), turbulence, UVR monthly doses, UVR maximum daily doses around 1 April and 1 May etc.) were correlated against cod recruitment (ICES 0-year class strength 1967-2000), as well as abundance of *Calanus Finmarchicus* (1984-2001). A strong positive correlation was found between cod recruitment on one side and GSI, turbulence and UVR maximum daily dose around 1 May on the other side. There is also a strong positive correlation between the recruitment and the NAO index two years earlier.

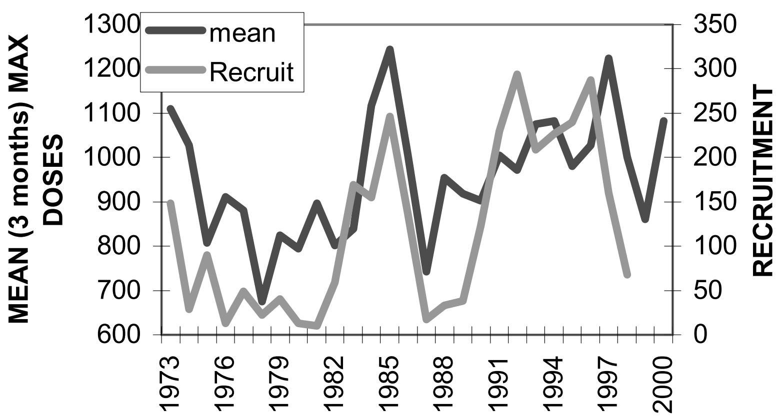

Figure 3. Cod 0-year class strength (light grey) from ICES and UVR maximum daily dose on 1 May (± 5 days) at Skrova, Lofoten (dark grey).

The strongly significant positive correlation between UVR maximum doses around 1 May and cod recruitment, shown in Figure 3, was a major surprise, contradicting the basic work hypothesis of the project, namely that UVR has an adverse impact on cod eggs and larvae. There is no obvious dependence between UVR maximum dose and other geophysical parameters correlating with cod recruitment, such as the GSI, so that one has to consider the found correlation as a true one. However, a plausible mechanism has not been found so far. What further complicates the situation is the fact that the cod recruitment correlates most clearly with UV-B dose, not with UV weighted with a cod egg mortality action spectrum. The spatially resolved satellite climatologies were used for correlation studies between UVR doses from limited regions and zooplankton population and recruitment. Due to the limited number of data pairs, the correlations found are not significant at the 95% confidence level, but the coefficients are all negative.

Acknowledgments

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Marine Ecosystem Responses to the Warming of 1920s and 1930s

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Introduction

In the 1920s and 1930s there was a dramatic warming of the air and ocean temperatures in the northern North Atlantic (Rogers, 1985; Johannessen et al., 2004). This warm trend continued through to the 1950s or 1960s, with the timing of the decline varying with location. These high temperatures match, and in some cases exceed, the present day warming. Large and significant changes in the marine ecosystems occurred as a result of the earlier warming. Some of these changes are documented herein for comparison with present warming and as a guide to predicting future effects of anthropogenic-induced climate change.

Ecosystem Responses

This warming lead to dramatic changes in the distribution, abundance and migration patterns of marine flora and fauna. Some examples of the observed responses from five different regions of the North Atlantic are presented.

West Greenland

The most well documented change was the increase in abundance of Atlantic cod (*Gadus morhua*) off West Greenland. From the late 1910s to the early 1930s, they not only increased in numbers but spread gradually northward from their location near the southern tip of Greenland prior to the warming to Upernavik in West Greenland after the warming was fully established, a distance of over 1500 km. This is believed to be due to both increased transport of larvae from Iceland and better survival of those once they reached West Greenland waters (Jensen, 1949). The increased cod abundance led to the development of a large cod fishery, which replaced seal fishing as the main industry in the country, and it remained dominant until the collapse of the cod in the 1970s. Jensen (1949) also documented changes in many other species. These included haddock (*Melanogrammus aeglefinus*), halibut (*Hippoglossus hippoglossus*), and herring (*Clupea harengus*), which also spread northward and whose abundances increased. On the other hand, colder-water species such as capelin (*Mallotus villotus*) were found not to migrate as far south along the coast as before and their abundance in southwestern Greenland decreased while it increased in the north as far as Thule. In northwestern Greenland, white whales (*Delphinapterus leucas*) and narwhals (*Monodon monoceros*) arrived earlier and left later on their annual migrations. New immigrants came to Greenland including tusk (*Brosmius brosme*), ling (*Molva vulgaris*), witch (*Pleuronectes cynoglossus*) and the jellyfish (*Halopsis ocellata*), probably through advection from Iceland.

Iceland

Prior to the warming in the 1920s, the Atlantic cod spawned almost exclusively off the south coast of Iceland. As the waters warmed, cod spawning spread northward until there were major spawning locations completely surrounding Iceland (Sæmundsson, 1934). Capelin, which also principally inhabited the southern waters off Iceland prior to the warming, moved to the north coast with the rise in temperatures and became scarce on the south coast. Being a major prey for adult cod, the absence of capelin on the south coast resulted in a decrease in the condition of cod that remained there. Several warm-water species, such as basking sharks (*Selache maxima*), tunny (*Orcynus thynnus*), mackerel (*Scomberus scomberus*) and sunfish (*Orthagoriscus mola*), appeared occasionally and sometimes frequently in Icelandic waters, while previously they had been rare or absent altogether (Sæmundsson, 1934; Fredriksson, 1949).

Faroe Islands

Surrounded primarily by Atlantic waters, none-the-less the Faroes also experienced ecosystem changes during the warm period. Most noticeably was the invasion of the Atlantic horse mackerel in relatively large numbers (Tåning, 1949). In addition, several other warm water species became occasional visitors to the Faroe Islands, including swordfish (*Xiphias gladeus*), twaite shad (*Alosa finta*) and pollock (*Pollachias pollachias*) (Cushing and Dickson, 1976).

Barents Sea

With the warming in the 1920s and 1930s, cod appeared in large quantities on Bear Island Bank, which resulted in the reestablishment of a cod fishery there after an absence of almost 40 years (Blacker, 1957). Cod, as well as haddock, expanded eastward to Novaya Zemlya. The abundance of Norwegian spring-spawning herring increased in parallel with the temperatures recorded at the Kola section, a hydrographic monitoring section off Northern Russia (Toresen and Østvedt, 2000). A herring fishery developed along the Murman coast of Russia, whereas previously this species was almost unknown in this region (Beverton and Lee, 1965). The capelin feeding migration is believed to have also spread farther north and east in the Barents Sea during the warm period as they migrated to and from the Polar front that separates the cold, low salinity Arctic waters from the warm, high salinity Atlantic waters. The responses were not limited to fish. Russian studies revealed a retreat of Arctic benthic species and an increase in the number of boreal species along the Murman coast such that the relative amount of boreal species doubled between the period prior to and during the peak of the warming (Nesis, 1960).

Svalbard

Atlantic cod spread northward into the area off West Svalbard in large numbers during the 1920s (Beverton and Lee, 1965). Comparison of benthos prior to the in the 1930s with those of the 1950s indicated that Atlantic species spread northward by approximately 500 km (Blacker, 1957). It was suggested that this was a result of an increasing effect of the Atlantic waters in the region.

Conclusions

With the warming of the waters during the 1920s and 1930s, significant changes in the distribution, migration patterns and abundances of numerous species occurred in the Northern North Atlantic. Most prominent was a northward movement of many species with a retraction of Arctic species and a spread of boreal and subtropical species. The most significant change occurred off West Greenland where the economy of the region switched from seal fishing to one based almost exclusively on Atlantic cod. While more intense fishing pressure exists today and no doubt does and will influence the ecosystem responses, it is clear that much can be learned from examining the response to past climate changes.

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Biological Implications of Arctic Change

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Introduction

The detection of biological change in the Arctic marine environment can be expected to coincide with recent patterns of high-latitude environmental change, including a seasonal reduction in the extent and duration of sea ice, increased seawater temperature, and changing hydrographic conditions (e.g. Serreze *et al.,* 2003; Overland and Stabeno, 2004). The shallow, productive features of the Bering Strait region in the Ameriasian Arctic may accentuate its role as a sentinel indicator of global change effects (Grebmeier and Dunton, 2000). Ecosystem change on the shallow shelves of the northern Bering and Chukchi seas are intimately connected to systems further to the north (Figure 1). Current studies undertaken as part of the Bering Strait Environmental Observatory (BSEO; http://arctic.bio.utk.edu/AEO/index.html) are occupying time series sites in the northern Bering and Chukchi seas to evaluate basic hydrographic and biological parameters. The Western Arctic Shelf-Basin Interactions (SBI; http://sbi.utk.edu) project is also investigating the production, transformation and fate of carbon at the shelf-slope interface in the northern Chukchi and Beaufort seas in the context of Arctic environmental change.

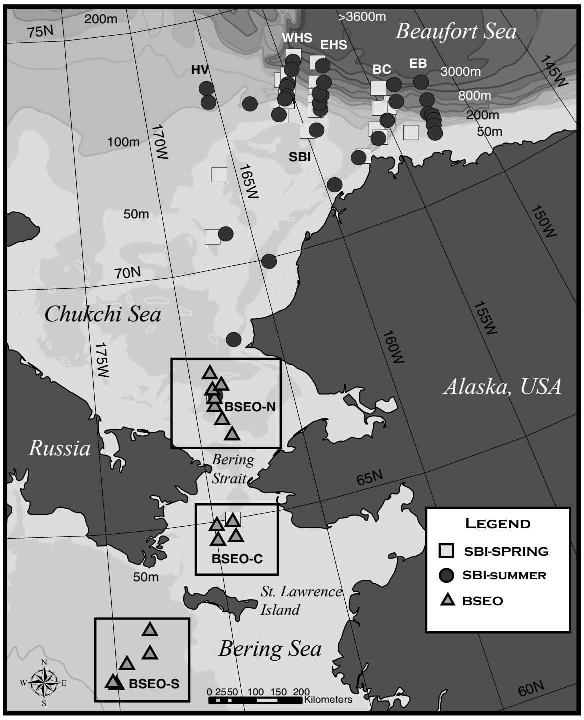

Figure 1. Location of time series oceanographic data for the Bering Strait region maintained by the Bering Strait Environmental Observatory (BSEO) and the western Arctic Shelf-Basin Interactions (SBI) study area. The BSEO sites are designated as BSEO-S (south of St. Lawrence Island), BSEO-C (Chirikov Basin) and BSEO-N (north of Bering Strait). The SBI transects are HV (Herald Valley), WHS (West Hanna Shoal), EHS (East Hanna Shoal), BC (Barrow Canyon) and EB (East Barrow).

Recent studies show that the northern Bering Sea is shifting towards an earlier spring transition between ice-covered and ice-free conditions, with coinciding changes in both primary and secondary trophic level production (Stabeno and Overland, 2001). These changes could have dramatic impacts for higher-trophic level fauna, including some species such as benthic-feeding walrus, bearded seals, gray whales and diving sea-ducks that are of cultural and subsistence significance to Arctic Native residents. Studies in the northern Bering and

Chukchi seas over the last two decades provide many indications of ecosystem change. The tight pelagic-benthic coupling observed between seasonal water column carbon production processes and underlying short- and long-term benthic carbon transformation processes provide a “footprint” in the sediments of persistent ecosystem events and subsequent time-series changes. Pelagic-benthic coupling can be studied via underlying sediment processes on various time scales. Sediment metabolism can be an indicator of weekly-to-seasonal carbon depositional processes, while benthic faunal populations can act as multi-year, long-term integrators of a variety of marine processes.

Methods

Biological time series sites south of St. Lawrence Island (BSEO-S), in the middle of Chirikov Basin to the north of St. Lawrence Island (BSEO-C), in Bering Strait, and just north of Bering Strait in the southern Chukchi Sea (BSEO-N) have been occupied since the late 1980’s and in some cases, earlier (Figure 1). Hydrographic measurements of seawater temperature and salinity, along with nutrients and chlorophyll content, were made at these sites using CTD/rosette systems. Hydrographic analyses, benthic population structure, sediment tracer analyses, biomass and sediment oxygen uptake rates that were measured during these studies have been documented elsewhere (e.g., Grebmeier and Cooper, 1995; Cooper *et al.*, 1997; Cooper *et al.*, 2002). Similar methods were utilized during the SBI studies from 2002-2004 (Figure 1).

Results and Discussion

An overall decline in both sediment oxygen uptake (an indicator of carbon supply to the sediments) and overall benthic standing stock from the 1980’s to the present has occurred in the Bering Strait region, with probable impacts upon higher trophic organisms that are dependent upon benthic prey. For example, declining bivalve populations south of St. Lawrence Island suggest that the decline in the bivalve prey source could be playing a role in population declines for the spectacled eider (Lovvorn *et al.*, 2003). Other studies indicate that a change in hydrographic forcing and nutrient supply is limiting primary production in the region (Figure 2; Grebmeier and Dunton, 2000; Grebmeier *et al.,* in prep). In addition, recent

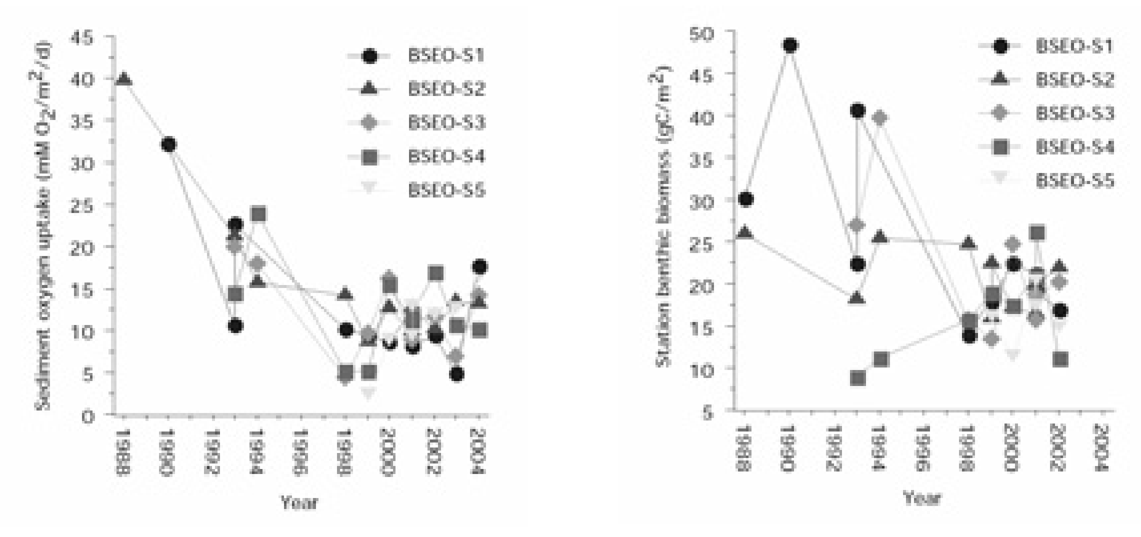

Figure 2. Time series measurements of total sediment oxygen uptake (an indicator of carbon supply to the benthos) and benthic biomass in the region southwest of St. Lawrence Island in the northern Bering Sea (BSEO-S).

studies of gray whale feeding areas and benthic time series measurements data in the Chirikov Basin also indicate a decline in the benthic amphipod prey biomass in the region over the last decade, with indications that gray whales are feeding predominantly north of Bering Strait (Moore *et al.,* 2003). Recent data also indicate gray whales are feeding in new areas along their migration path to obtain food without reaching historical feeding areas in the Bering and Chukchi Seas (Grebmeier *et al.*, unpubl. data).

Thus, biological populations are exhibiting ecosystem change on the shallow shelves of the northern Bering and Chukchi seas, and this ecosystem is intimately connected to the larger Arctic systems further to the north. Current studies as part of the SBI project at the shelf-slope interface in the northern Chukchi and Beaufort Seas are downstream of these productive shallow western Arctic shelves. In these recent studies (2002-2004) sediment oxygen uptake, nutrient flux and benthic faunal populations were highest on the Chukchi shelf, with rates decreasing in the Beaufort Seas as well as from the shelf to deep basin in all transect lines (Grebmeier and Cooper, 2004, submitted). Sediment nutrient exchange indicates high levels of silicate and ammonium effluxing from the sediments in the Chukchi and Beaufort shelves and being transported into the deep basin at the level of the Pacific-influenced Arctic upper halocline. In addition, Barrow Canyon is a key exchange site for both particulate and dissolved carbon. Any change in hydrographic forcing and benthic processes on the productive northern Bering and Chukchi shelves will directly impact carbon and nutrient export from the shelf regions to the deep basin. These current and planned shelf-basin studies are providing key baseline data for research planning efforts on Arctic environmental change (see Arctic Ocean Sciences Board; http:www.aosb.org), International Conference on Arctic Research Planning II (http://www.icarp.dk/), and planning for the International Polar Year (http://www.ipy.org/).

Acknowledgement

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Ecosystem Changes in High Arctic Marine Ecosystems

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Since the late 1970s, an overall decrease in sea ice distribution has been observed in the Arctic. This decrease has led to prolongation of the ice-free period off the north coast of Russia, in the Greenland Sea, the Barents Sea, and the Sea of Okhotsk. Higher atmospheric temperatures will increase the transport of water vapor toward the North Pole, resulting in an increase in precipitation and freshwater (snow) supply to high latitudes. An overall presentation is given of results obtained in the integrated ecosystem study CAMP (Changes in Arctic Marine Production) in the high-Arctic fjord, Young Sound (75°N), NE Greenland. The aim of this study is to link biological production to sea ice and hydrographic conditions in order to predict how expected changes in snow, ice and hydrographic conditions will affect high-Arctic marine ecosystems in the future.

Young Sound is a deep-sill East Greenland fjord similar to numerous other large, deep fjords in the region that often penetrate hundreds of km inland. The fjord is connected to the East Greenland Current, which consists of polar water in the upper 150-200 m and carries large amounts of sea ice with it. Sea ice begins to form in September, growing to a thickness of 1.5 m before it breaks up in mid-July the following year. The average ice-free period (1958-1990) is 80 d but has shown a dramatic increase during 1990-2004 with up to 140 ice-free days during 2003. Typically, meltwater from the Greenland Ice Sheet and rivers drain into the inner parts of the East Greenland fjords. The total freshwater discharge in Young Sound takes place over a 3-month period during June-September. During the ice-free period freshwater input and mixing by wind and tides result in an estuarine circulation, by which lighter water of salinity <30 is moved seaward above denser water from the East Greenland Current with salinities of 31.5 – 34.4.

Following the break-up of ice, the immediate increase in light penetration to the water column causes a steep increase in primary production. In the shallow parts covering the photic zone (0-40 m), benthic primary producers dominate primary production. As a minimum estimate, primary production fixes 50 g C m^{-2} yr^{-1}, of which phytoplankton assimilates 12%, sea ice algae <1%, benthic macrophytes 46% and benthic microphytes 41%. Tight coupling between primary producers and grazers has been observed in these high-Arctic areas. Grazing in the water column, primarily by copepods, leads to pulsed vertical export of organic matter to the sea floor where benthic animals and microbes are responsible for further degradation of the organic matter and regeneration of nutrients. In the shallow parts of the fjord, carbon fixation by algae balances carbon consumption resulting from grazing, mineralization and burial. Bivalves constitute an important part of the benthic fauna, especially in shallow waters (<40 m) and represent a plentiful inshore food resource for walruses. As a solid layer of ice covers Young Sound, except during the short open-water period, the fjord is inaccessible to walruses most of the year. Thus, the population of walruses in the area is only able to consume <3% of the standing stock of bivalves or less that half of the annual somatic bivalve production.

In the deep, central parts of the fjord the only primary producers are phytoplankton and sea ice algae, which represent a carbon fixation of 10 g C m^{-2} yr^{-1}. In contrast to the shallow-water parts of the fjord, the carbon consumption of 49 g C m^{-2} yr^{-1} in the deep parts due to grazing, mineralization and burial differs greatly from the carbon production from phytoplankton. The difference of 39 g C m^{-2} yr^{-1} is balanced by the input from the Greenland sea (15-45 g C m^{-2}

yr^{-1}). The input of organic C from land to the outer regions of the fjord accounts for only 2-3% of the total input, although, in the short term, it may be responsible for a substantial fraction (59%) of the settling material in connection with peak discharge in the rivers. Overall, input from the Greenland Sea is essential to sustain the ecosystem in the fjord.

A regional atmosphere-ocean model predicts a temperature increase of up to 6-8°C at the end of this century (2071-2100) that will lead to increase in freshwater runoff, thinning of the sea ice, and an increase in ice-free conditions from 2.5 months to 4.7-5.3 months in Young Sound. Evaluation of the effect of increased freshwater flux into the fjord reveals that in fjords dominated by entrainment mixing, the surface-layer thickness (e.g. upper low-salinity layer) will change only marginally. In contrast, the transport of saltwater from the Greenland Sea to Young Sound below the halocline will increase significantly due to increased estuarine circulation. An increase in the ice-free period will enhance biological productivity in the area due to increased light availability for primary producers. Because the surface layer thickness will have changed only marginally by the end of the century, the phytoplankton bloom will continue to occur in a subsurface layer, but as net input increases, production will benefit from an increased import of nutrients and organic matter from the Greenland Sea. Improved food availability will stimulate bivalve growth and production in the area. Furthermore, an increase in the ice-free season will prolong the period in which birds and marine mammals, e.g. walruses, have access to the food-rich coastal area and thus improve their foraging conditions.

The predicted changes in temperature, ice-free conditions, and precipitation in the area at the end of this century suggest that physical conditions in Young Sound will become more similar to present-day conditions farther south, e.g. at Kap Tobin (Fig. 1). Thus, the area extending from Young Sound and a few hundred km south represents a climate gradient reflecting this century's climate change. We suggest that investigations along north-south transects in this region may be highly valuable in evaluating adaptations of biological processes and species to different physical settings brought about by future climate change in the Arctic.

Supplementary information can be found on the Internet:

www.dmu.dk/LakeandEstuarineEcology/camp

www.zackenberg.dk

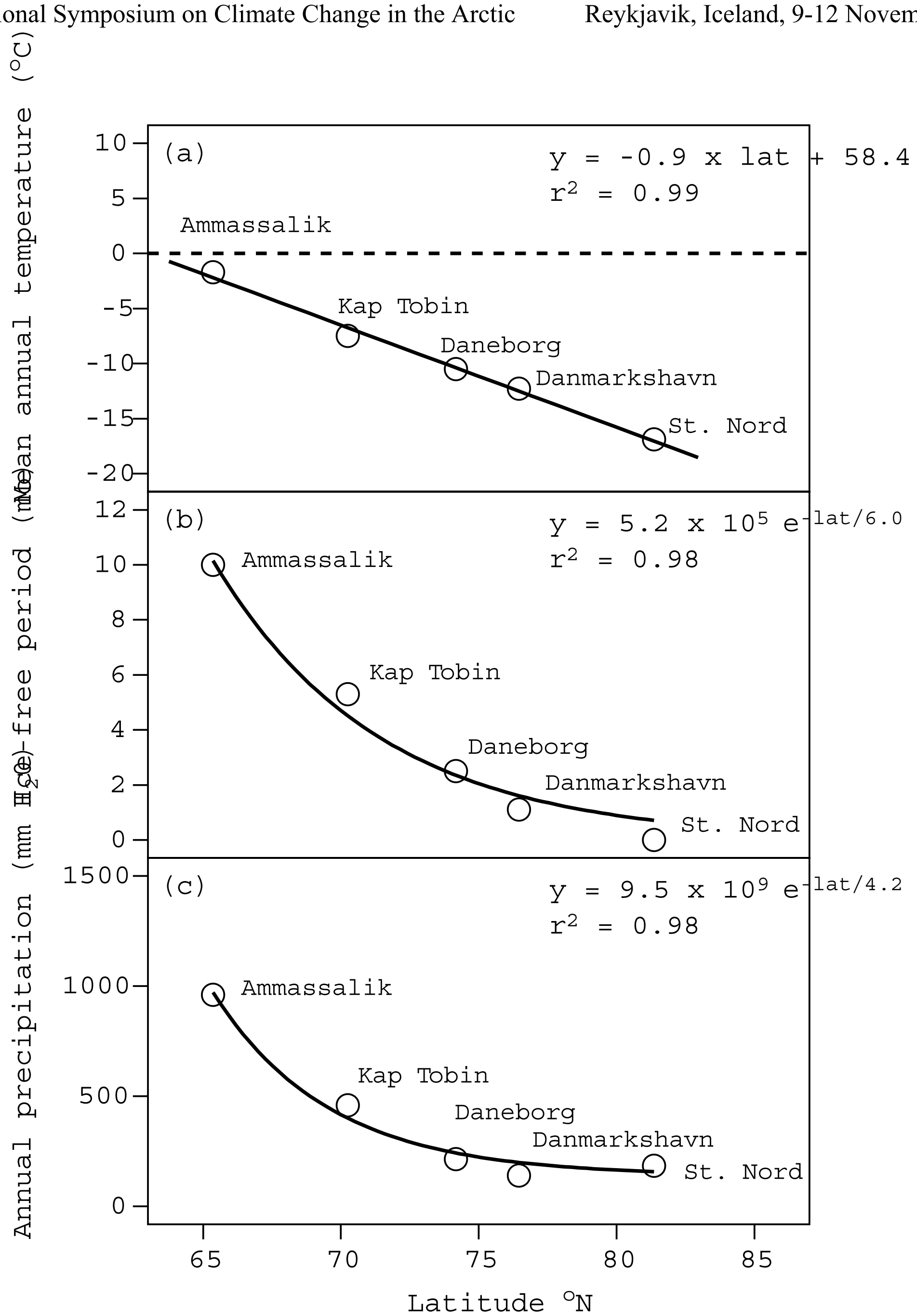

Figure 1. (a) Mean annual temperature in Northeast Greenland versus latitude. (b) Annual ice-free period versus latitude. (c) Mean annual precipitation versus latitude. Daneborg is situated in the outer region of Young Sound.

Anadromous Arctic Fishes and Impacts of Climate Change

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There are several Arctic species within the families Acipenseridae, Coregonidae, Gasterosteidae, Osmeridae, Petromyzontidae and Salmonidae that exhibit anadromous behaviour i.e. spend part of their lives in the marine environment and migrate to freshwater to spawn. Two species, Arctic cisco (*Corengus autumnalis*) and rainbow smelt (*Osmerus mordax*) are considered to be obligatory anadromous (Craig, 1989), that is all individuals in a population reside for some time in a marine environment before they reproduce. However, most anadromous species in the Arctic are considered to be facultative (Craig, 1989) since all individuals of a population do not necessarily migrate to sea. Typically, anadromous behaviour is most dominant at nothern latitudes (McDowall, 1987) because oceans are more productive than freshwater habitats in temperate zones (Gross *et al.*, 1988). For a number of facultative anadromous species (e.g. Arctic char, dolly varden, brook trout, brown trout, 3-spine sticklebacks), anadromous behaviour ceases towards the southern portion of the species distribution range (several references in McDowall, 1987). It is likely that facultative anadromous species exhibit such behaviour in polar regions to take advantage of marine coastal productivity and escape extreme oligotrophic conditions that typify Arctic lake systems. Generally, individuals of a population that exhibit anadromous behaviour have a larger maximum size and higher maximum age, indicating some benefit to seaward migration and feeding (Gross, 1997).

Overall projected impacts of climate change on Arctic lakes suggests that productivity of these limited systems will increase. Ice-off is expected to occur earlier in the season and ice formation to occur later, thereby extending the ice-free, growing season. As a result, primary productivity should increase. In addition, reduction of the permafrost will increase the supply of organic material and nutrients from terrestrial systems which should also increase primary productivity. Productivity in streams is also expected to increase. If increases in primary productivity cascade to secondary and tertiary productivity, fihs populations should initially benefit with increases in abundance and size. However, there will be a carrying capacity at which growth and abundance will be regulated by density. Ice cover on Arctic lakes is expected to be thinner allowing increased solar radiation penetration during fall and spring. Photosynthetic production of oxygen during these times will increase and will reduce the potential of winter fish kills. If the benefits of increased productivity and reduced winter fish kills in freshwater systems (lakes and streams) persist, then facultative anadromous species may actually exhibit less and less anadromous behaviour if the benefits for migrating to coastal areas for summer feeding are outweighed by the benefits of remaining in freshwater systems. Nordeng (1983) reported that when the freshwater food was experimentally increased, the incidence of anadromous migration by Arctic char decreased.

The variability associated with projected changes in productivity is uncertain. The anadromous species found in the Arctic are typically long-lived (20-50 years) compared to other Arctic fish species. Longevity benefits a species by ensuring a relatively long reproductive cycle, which minimises the risk that prolonged periods (5-15 years) of unfavourable environmental conditions with result in the loss of a spawning stock (Leaman and Beamish, 1981). The anadromous forms of Arctic fish species are long-lived (longer than their freshwater forms) and are likely suited to cope with increased variability. Initially as environmental conditions improve, successful spawning episodes will increase in frequency. Anadromous fish that are short-lived (<20 years) will likely exhibit more variability in abundance trends with increased variability in environmental conditions.

The anadromous species found in the Arctic also inhabit streams or rivers in addition to lakes. Projected climate impacts on Arctic hydrology suggest that runnoff will be driven by increased precipitation and will no be as seasonally variable. There will be enhanced winter flow and reduced summer flow. Warmer conditions will reduce the length of winter and shorten ice season along with a reduction in the thickness of ice. Streams that were previously frozen solid will retain water beneath ice. This will benefit anadromous species that utilize streams for winter habitat. Overwintering habitat is critical for Arctic species and are typically of limited capacity (Craig, 1988). However, the shortened ice season and thinner ice will redcuce the severity of ice-jamming. This will have implications for productive river deltas that require flooding. There are several anadromous species, such as Arctic cisco, that rely on deltas as feeding areas, particularly in spring (Craig, 1989).

There are a number of anadromous species whose nothern limits of distribution will likely expand to include many regions within the Arctic. Pacific salmon species will likely expand into Region II. Sockeye and pink salmon have already been recorded from Banks Island, NWT, Canada which is outside their normal range of distribution (Babaluk *et al.*, 2000). Similarly, anadromous species such as Atlantic salmon, alewife, brown trout and brook trout could also extend their northern range of distribution into Regions I and IV. Invasion of new anadromous species to Arctic regions will likely have negative impacts on species already present.

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Char as a Model for Assessing Climate Change Impacts on Arctic Fishery Resources

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Introduction

Arctic char (*Salvelinus alpinus*) is a circumpolar species that occurs across a wide latitudinal range (~85°N to ~45°N) from the High Arctic to temperate areas (Johnson, 1980). Given this distribution, char appear particularly flexible with respect to life history, ecology, and adaptability to a variety of conditions. In the north, char exhibit sea-run (migratory, anadromous) and freshwater (resident, non-anadromous) life histories with different types variously occupying lakes, rivers, estuaries and nearshore environments seasonally and/or throughout life (Klemetsen et al., 2003). Wherever they occur, but especially in northern areas where they are often the only fish species present in freshwaters, char may also differentiate into a variety of co-occurring growth or morphological forms. Such differentiation may arise for ecological or genetic reasons, and when coupled with life history variability adds complexity to attempts to understand northern aquatic ecosystems. For example, within a particular lake-river system with sea access, some non-anadromous individuals may assume the role of apex predators as cannibals consuming other char, others may exploit lower trophic levels in pelagic, littoral or benthic areas of the lakes, and still others may migrate annually to and from the sea to feed during summer in estuarine and nearshore areas. The various traits described above all suggest that char populations will variously integrate at several levels many of the effects of climate variability and change (CVC), and biologically they appear to be ideal for investigating and monitoring CVC effects on arctic aquatic ecosystems.

In addition to these biological advantages of using char to monitor CVC effects, they are important in arctic freshwater and nearshore fisheries, and of emerging importance in aquaculture. In the Canadian North, significant commercial char fisheries occur along the Labrador coast (DFO, 2001) and at Cambridge Bay (Victoria Island) (DFO, 2004); trophy sport fisheries occur in many areas with perhaps the best known in Tree River (Moshenko et al., 1984); and, Aboriginal subsistence fisheries occur throughout the area (Huntington et al., 1998). Similar levels of use occur throughout the Arctic. Thus, char are important culturally, economically and for sustenance. As a result, considerable management and research effort has been, and will continue to be, directed towards understanding population perturbations, impacts and ensuring sustainability. The importance of char requires the development of both appropriate projections of potential CVC effects and management responses to CVC issues to ensure conservation and sustainability under all possible future climate scenarios.

The biological traits and importance noted above make char an ideal organism for understanding higher-level effects of CVC on both the ecological and human systems of the Arctic. The aims of this work are to: 1) examine the relevance of char generally for assessing CVC impacts; 2) provide some examples of studies of CVC-biological interactions using char; and, 3) explore the utility of char in research and future monitoring programmes to assess CVC impacts, with particular emphasis on those that can be at least partially implemented by local communities and fishers.

Methods

Establishing reasonable understanding of climate-driven temporal variation in a char population and differentiating this from other factors such as exploitation are major undertakings for any single population. Further, a key handicap in understanding climate-related effects on char populations is the paucity of temporal and spatial studies linking climate variables, arctic aquatic ecosystem processes and char population biology. These both hamper our ability to project future states, thus alternative approaches must be found to understand char-CVC interactions and to develop plausible scenarios for char. Various approaches for linking char biology and climate variation are available (see Box 7.8 in Wrona et al., 2005), but most interactions are summarised to the first order only (e.g., temperature effects on individual fish with no extrapolation to consequences for the population). Despite the elegance of the experiment, monitoring char population changes over the course of climate change for >100 years is too long a time horizon to be immediately useful in developing effective adaptive responses useful for conservation and management. Thus, similar to studies of past climate variation, proxy measures are necessary to estimate the effects of CVC on char populations. We offer two examples of recent and ongoing studies aimed to redress some of these needs.

Conclusions

Labrador Char Temporal Variation: Power et al. (2000) examined environmental associations with char population parameters. Biological data (mean catch at age, length, weight) from a 21-year time series were matched to climate parameters (air temperature [T], precipitation, sea surface T, salinity). Summer air and sea surface T's affected the biological system on an annual basis likely by increased nearshore marine productivity which for individual fish led to increased weight, length and growth, and thus to better overall condition for the population. Winter precipitation the season before the first summer of life of individual fish increased the snow pack and decreased seasonal freezing thus indirectly provided more overwintering habitat; this led to increased overwinter survival thence to more fish in the population. Similarly decreased energetic demands over winter increased growth, leading to earlier recruitment to the fishery (measured as lower age at catch). Finally, summer air T and precipitation during the fourth year of life (~first year at sea for most char) increased nearshore nutrient loading and productivity which led to increased growth and survival of this age class as seen in increased weight and decreased age of fish at catch. Thus, where data exist climate variability is important for understanding inter-annual dynamics of char populations. The potential coupling of these findings with climate change projections at the regional and sub-regional level may also allow for extrapolation of long-term future scenarios for char fisheries in many areas of the Arctic.

Latitudinal Variation in Char Population Parameters: We have assembled biological data for approximately 100 char populations spanning the latitudinal range of char in eastern North America from Maine to northern Ellesmere Island (unpublished data). This latitudinal range can be divided into Temperate, Sub-Arctic, Arctic and High Arctic zones that differ greatly in basic climate parameters (e.g., annual mean daily T is >0, -3 to -10, -10 to -17, and -20 ^{o}C respectively). Thus, climate variation across latitudes can be used as a proxy for future climate change and within- and between-population analyses of char biological parameters may offer clues to both the range and the direction of future responses of char populations. For example, fecundity, a measure of reproductive potential, when corrected for individual size of the fish showed significant negative linear trends with increasing latitude. This suggests that a) this measure of char reproductive capacity will shift with climate change with higher latitude populations becoming more fecund as local areas warm; and, b) char forms differ in the strength of their response, with anadromous and dwarf types possibly responding to a greater degree than the normal lacustrine type, thus loss of the latter type especially at lower latitudinal areas is a real possibility.

The examples outlined above suffer from two fundamental flaws – insufficient basic data and poor understanding of causal linkages between environmental and biological parameters. When linked to imprecision of climate change scenarios, our ability to project reasonable future scenarios for aquatic biological resources such as char is severely compromised. Redress of this is required and we offer here some elements of a strategy for monitoring and ground-truthing CVC impacts on char populations. First, a programme must be developed to monitor parameters of the fish population, their aquatic environments and climate over space and time, and it should be conducted in the context of biodiversity of char present in the area so as to increase precision in our understanding. This can best be implemented for a few, national and international, linked arctic sites that span the latitudinal and regional range for char. Studies must be coordinated with the same protocols used over the longer term to document shifts in local char populations and ecosystems as climate change develops. Even a modest programme for the Arctic is a huge undertaking, thus a manageable programme can best be conducted by enlisting the aid of local communities, resource users and arctic residents to gather both the necessary local biological and climate data. Second, in order to provide much of the interpretative context and in-depth understanding for these monitoring data, to differentiate change from variability for biological parameters, and to ascribe proper causation for such change, a substantive parallel research programme is required to investigate char biology and ecology and climate system linkages to these. The monitoring programme would provide many of the required temporal and spatial data whereas the research programme would provide detailed understanding of general effects of climate parameters on char populations, assessments of char responses to CVC effects, and verification of projections over time. Programmes such as these would offer great promise for understanding and preparing for CVC impacts on aquatic resources across the Arctic.

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Trend Coincidence of Pink Salmon Catch Dynamics among the Odd-years and Even-years Populations as an Evidence of Large-scale Physical Factors Effect

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Introduction

Coastal catch dynamics remained one from the basic index of Pacific salmon stock conditions until the present time. Several cyclic patterns of long-term dynamics of Pink salmon abundance were previously revealed from the catch data and could be considered as generally recognized regularities. Biannual cyclic recurrence of spawning approach and catch is inherent for the most of pink salmon regional groups due to interchanging of the odd-years and even-years populations. These populations usually differ markedly by level of spawning stock abundance and progeny, consequently. Due to long-term domination of even-years or odd-years population, the opposite dynamics of Pacific salmon stocks exist even in some neighboring regions, i.e. western and eastern Kamchatka coast.

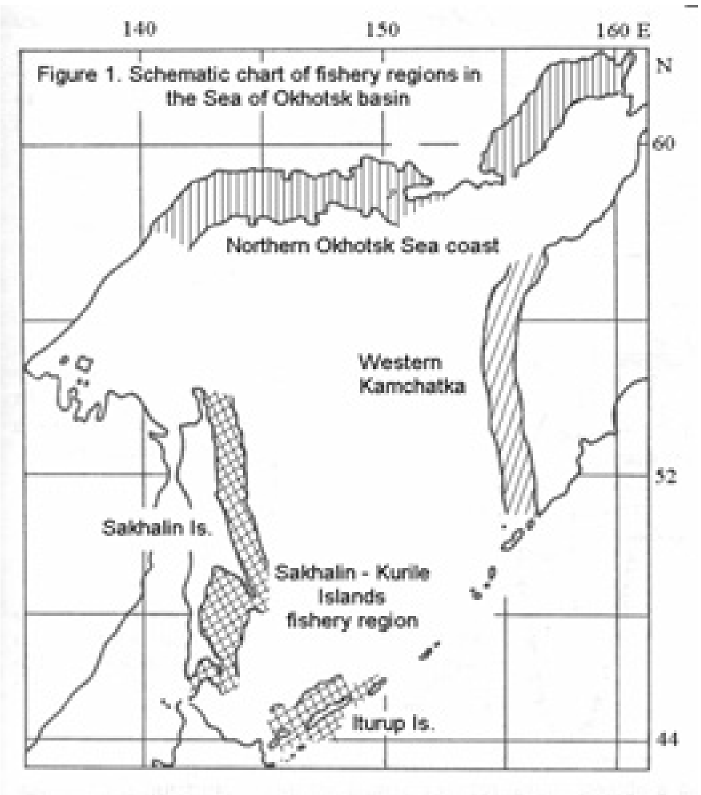

Figure 1. Schematic chart of fishery regions in the Sea of Okhotsk basin

Several long-period oscillations of pink salmon stocks were revealed as in the different fishery regions, as in the North Pacific on the whole (Beamish and Bouillon, 1993; Chigirinsky, 1993). The oscillation periods were estimated as close to so called "planetary cycle" in 50 - 60 years, in some studies - as close to 11-years solar cycle (Sukhanov, 1997). For increasing catch forecast correctness, it is necessary to reveal the most important factors among the natural and anthropogenic ones, which generates the abundance fluctuations, and also "change of dominants" as a specific event for the pink salmon stock dynamics. It means sharp drops in abundance of prevailing population far below the average abundance level of population of adjacent years.

Methods

For this purpose, the abundance dynamics of the odd-years and even-years pink salmon populations were analyzed separately by the methods, which make possible to level the differences in absolute values of the stock abundance. In our study, catch dynamics trends of pink salmon were calculated as arithmetical difference of "expected" catch calculated as the mean value of four previous years in the odd-years or even-years cycle and factual catch. Such technique of calculation was applied to suppress the noises and yield a clearer picture of the dynamics trend. The curves of the moving average are used for the graphic representation of the trends of long-standing dynamics; a smoothing factor of three was applied. All salmon catch values are given in metric tons (mt).

Results

Singular coincidence of catch dynamics among the almost independent odd-years and even-years populations was found for the Sakhalin – Kurile Islands fishery region (Figures 1, 2). Further analysis covered neighboring coastal fishery regions: the eastern Kamchatka, the western Kamchatka, and northern coast of the Sea of Okhotsk. No coincidence was found between catch dynamics of adjoining pink salmon populations on the eastern Kamchatka coast. Two other regions demonstrated satisfactory coincidence. However, the fluctuations there occurred rather smoothed in periods of pink salmon population depression and low catches: less than 1,000 mt in 1966-1982 on the northern coast of the Sea of Okhotsk, and less than 5,000 mt (with one year of exception) in 1958-1974 and, for odd years only, since 1987 until present time. This evening-out of trends negatively influence reliability of dependences between catch dynamics of odd-years and even-years pink salmon populations (Figure 3). Comparison between southern Sakhalin – Kurile Islands region and two northern regions suggests opposite dynamics of catch trend there. Such regularity was fixed previously for northern and southern salmon stocks along the west coast of North America (Gargett, 1997).

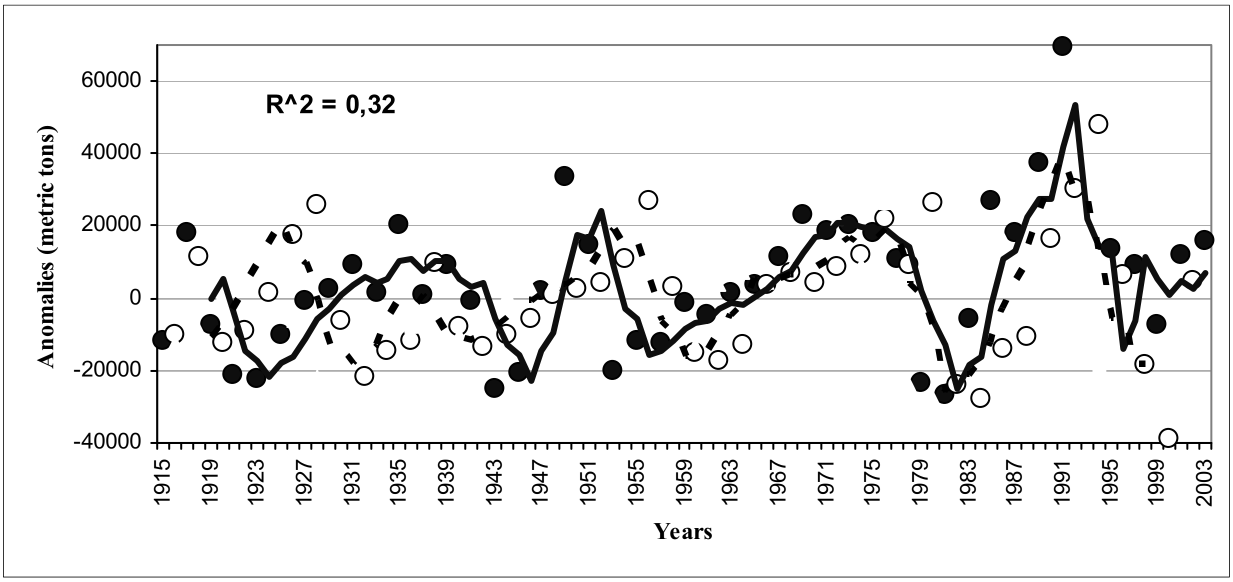

Figure 2. Anomalies of expected pink salmon catch value in the Sakhalin – Kurile Islands region, 1915 – 2003. Coincidence coefficient of trend curves for the odd-years (solid line, dark circles) and even-years (dotted line, open circles) populations is given. Trend curve for even-years population was moved back on two steps (four years) for the purposes of illustration.

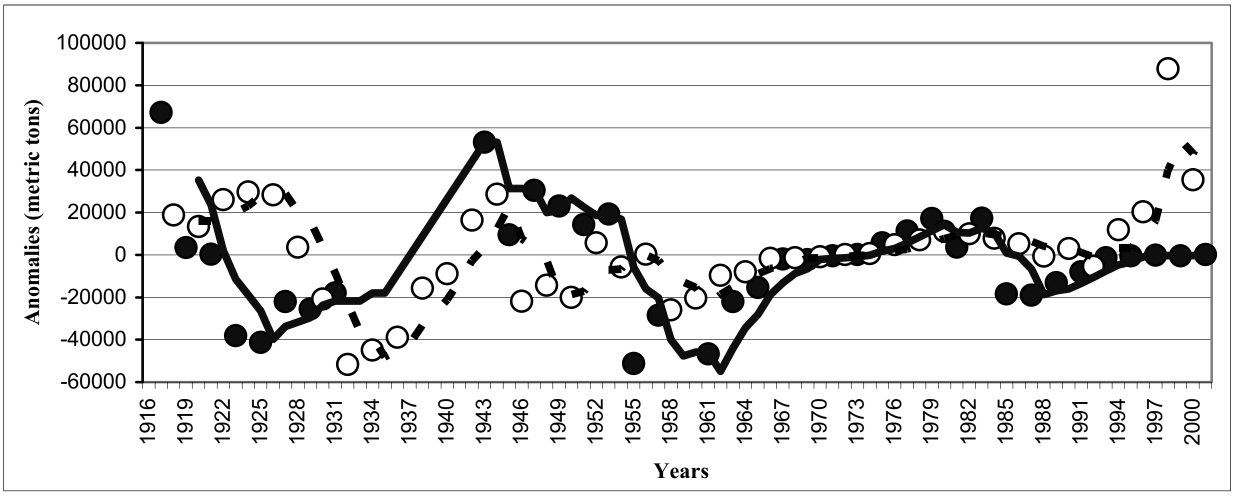

Figure 3. Anomalies of expected pink salmon catch value on the western Kamchatka coast, 1916 – 2001. Coincidence coefficient of trend curves for the odd-years (solid line, dark circles) and even-years (dotted line, open circles) populations is given.

For the Sakhalin – Kurile Islands region, alternation of uptrend and downtrend periods roughly coincided with 22-years (or double solar) cycle. Another feature is a rough coincidence of peaks of the odd-years trend curve with the generally recognized years of climate and oceanological «regime shifts» in 1950, 1976, and 1989. Coincidence of trend curves for the odd-years and even-years population has become more apparent in the second half of XX century (R^2 = 0.7) than for all data series since 1915. Among smaller fishery areas inside the Sakhalin – Kuriles fishery region, the Aniva Bay catch series demonstrated the highest coincidence of the trend curves (R^2 = 0.84). It creates expectations to develop a model for catch forecasting.

Discussions

The coincidence can not be explained by biological effects of odd-years and even-years population interference since fish of both generations spend a brief time in the same waters simultaneously. Divergence level along the genetic markers between them is higher than between the different local groups inside each of these generative lines (Glubokovsky, 1995). However, liability to the same trends of the salmon spawning approach dynamics in the even and odd years was recently noted for pink salmon on the Iturup Island, south-eastern Sea of Okhotsk (Kaev & Chupakhin, 2003). In their opinion, it indicated the fundamental similarity of interrelations in the system of "organism – environment" in the different pink salmon populations, together with the identical changeability of reproduction coefficients, which characterize survival in freshwater and marine life periods.

Observed relation between the pink salmon catch trends of even and odd years supposes an existence of the strictly determined internal response of populations to the periodic dynamics of global factor or the complex of factors, to a considerable extent determining the existing conditions of salmon reproduction and survival. A. Goryainov and T. Shatilina (2003) have found reliable correlation between sea-level atmospheric pressure in regions of Southern Asian Low and pink salmon catches in one year later. Variability of the Southern Asian Low effects monsoonal circulation of air masses and, then, synoptic conditions of salmon embryonic and early larval development during cold season. A. Gargett (1997) connected variation in the strength of the wintertime Aleutian Low pressure area with the water column stability characteristics, hence primary production value that further effect the forage success of salmon during marine life period.

Conclusions

Odd-years and even-years populations) of pink salmon in different regions of the Sea of Okhotsk coast demonstrate coincidence of catch dynamics through the whole existing catch series. That supposes an existence of the strictly determined internal response of salmon generative lines to the periodic dynamics of global factors, which effecting environmental conditions of salmon reproduction and survival. However, salmon dynamics trends obtain own regional features determined by local factors as natural, as anthropogenic ones.

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Palaeolimnological Evidence for Recent Climate Change in Lakes from the Northern Urals, Arctic Russia

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Introduction

General circulation models predict that warming in the Arctic will occur more rapidly than elsewhere, and there is growing evidence from palaeoclimatic studies that unprecedented climate warming has already taken place in many parts of the Arctic during the twentieth century (Overpeck et al., 1997). Lake sediment records in these regions are especially useful in identifying the extent of warming. Here we examine results from the Bol'shezemel'skaya Tundra in the northern Ural region of the Russian Arctic and assess evidence for climate change and also evaluate the impact of atmospheric pollution from local sources.

Methods

The recent sediments from two deep lakes, Mitrofanovskoe and Vanuk-ty, situated in the permafrost belt within the Bol'shezemel'skaya Tundra were studied for diatoms, chironomids, lead isotopes and spheroidal carbonaceous particles. The cores were ^{210}Pb dated. Rate-of-change analysis (Birks et al., 2000) was used to quantify the total amount of biostratigraphical change in both the diatom and chironomid assemblages per unit time. Summer, June, July, August and September temperatures from Vorkuta weather station (64º 01'E; 67º 17'N) were used to assess statistically the amount of variance in diatom and chironomid data explained by temperature. Similar methods to those described in Battarbee et al. (2002) were used to harmonise the climatic predictors and the response variables prior to least square regression. A LOESS regression (Cleveland et al., 1993) was used to smooth the climatic variables along a time axis.

Conclusions

There is evidence that recent diatom and chironomid changes at both Mitrofanovskoe and Vanuk-ty lakes have been driven, largely, by temperature. At Mitrofanovskoe Lake the evidence is clearer, the major compositional changes in diatom and chironomid communities are synchronous, and they are supported by the increase in total diatom accumulation rate and loss-on-ingnition. The chironomid-inferred summer temperature increases by c. 1° C during the last c. 100 years. The rate of change in diatom assemblages from the end of the 1960s is statistically significant at Mitrofanovskoe Lake, and the diatom changes are correlated with September air temperature changes during this period. We suggest that the mechanism behind the changes in the diatom community is related to an increase in the length of the ice-free season. The increase in deep-water chironomid taxa may also be in response to reduction in ice-cover and the consequent reduction in oxygen stress. At Mitrofanovskoe Lake the levels of global and regional pollution are relatively low, and the pollution signals are not correlated with the changes in diatoms and chironomids. We can therefore conclude that at

Mitrofanovskoe Lake the major driving force behind the diatom and chironomid changes since c. 1907 are temperature changes.

At Vanuk-ty Lake, diatom changes show a clearer response to temperature changes during the last 30 years whereas chironomid evidence is more ambiguous. The compositional changes in many planktonic and benthic diatom taxa are strongly correlated with August temperature and are coincident with the increase in diatom species richness and diatom production. Although these changes are predated by the rise in SCPs, it is unlikely that global and regional atmospheric contamination have had a pronounced effect on diatom composition as the overall pollution level is low and there is no evidence of acidification or eutrophication. We therefore suggest , that the mechanism behind the changes in diatom assemblages at Vanuk-ty Lake is similar to Mitrofanovskoe Lake and is dependent on temperature. However, there is no strong evidence for warming from changes in the chironomid fauna. One of the reasons behind an ambiguous chironomid evidence from Vanuk-ty Lake might lie in its complex morphometry with extensive shallow littoral and profundal zones, which allows for a coexistence of ecologically different chironomid groups.

Acknowledgement

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Climate, Snow and Hydrology in Tundra Ecosystems: Patterns, Processes, Feedbacks and Scaling Issues

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Introduction

Tundra extends over > 5.5 x 10^6 km^2 of the Arctic and has acted as a long-term carbon sink, sequestering atmospheric carbon in soils that today contain *ca.* 11% of total world carbon. Tundra is also characterised by a prevalence of high albedo surfaces (snow, ice and low tundra vegetation). Because of these attributes, tundra has a key role in moderating the global energy budget. In the future, however, warming of high latitude land areas is likely to reduce the spatial and temporal extent of high albedo surfaces and may switch tundra from a sink to a source of atmospheric carbon. Both impacts would generate positive feedback, enhancing the rate of future global warming.

Figure 1. Tundra mosaic (wet, mesic, dry ridge) at and beyond the tree-line at Abisko, N. Sweden.

Tundra exhibits hierarchically-scaled spatial heterogeneity, with plant community mosaics at landscape scales and variation in predominant mosaic elements at regional (Fig 1.) to Pan-Arctic scales. This heterogeneity reflects hierarchically scaled spatial and temporal environmental heterogeneity that has not yet been adequately captured by efforts to model the impacts of climate change upon Arctic tundra. This requires spatially- and temporally explicit process-based modelling at the landscape-scale. Such models must be underpinned by ecosystem studies that will provide the data necessary to achieve adequate representation of landscape processes and of their spatial and temporal variability.

Landscape-scale patterning of depth and duration of snow cover is the single most important meso-scale variable controlling biological systems in the Arctic, and is the primary determinant of landscape-scale ecosystem heterogeneity. Depth and duration of snow cover are consequences of interactions between landscape-scale variability in topography, including microtopography, and climate. Key facets of climatic variability include air temperature, precipitation (form and seasonal distribution), duration and intensity of solar radiation, surface albedo and surface energy balance, and windspeed and direction, all of which affect evapotranspiration, runoff and the distribution, depth and longevity of winter snow-pack. Duration of snow-lie also determines length of the plant growing season and is a primary determinant of the dynamics of soil temperature, soil moisture, depth of freezing and heat flux

(Fig. 2). Snow also stores water and nutrients that are released during the melt. Snow cover insulates the surface and reflects energy because of its high albedo, thus protecting vegetation from winter thermal extremes but also suppressing spring warming of the soil. Duration and extent of these seasonal effects have major impacts upon both plant communities and the soils with which they are associated, generating landscape mosaics ranging from exposed snow-free ridges to depressions characterised by deep snow accumulation. (Figs. 1, 2).

Through a series of measurements at complementary spatial and temporal scales, coupled with suitably robust up-scaling and modelling approaches, we aim to provide an improved spatially and temporally explicit representation of trace-gas and energy flux across the tundra landscape. The project builds upon existing work carried out in programmes in the American Arctic and the European Arctic. The key aims are three-fold: (i) A clarification of spatial

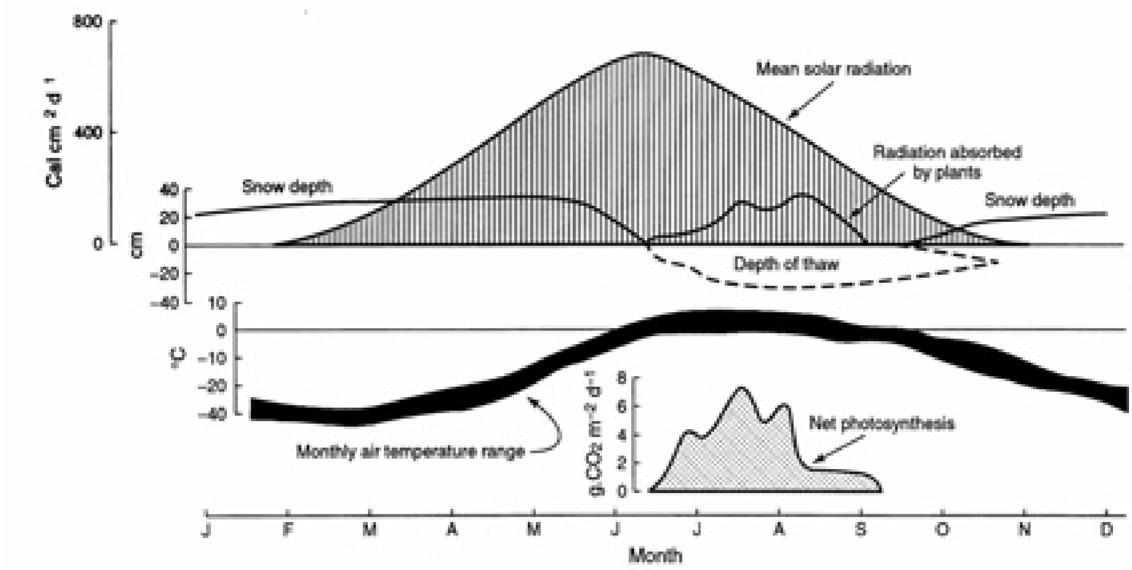

Figure 2. Snow-radiation-temperature-gas exchange interrelationships in northern tundra envionments (after Wookey PA (2002)).

scaling issues in trace-gas and energy exchange in tundra ecosystems. (ii) An improved understanding of the seasonal controls over trace gas and energy exchange, particularly the poorly-studied winter and early spring period; (iii) The provision of a northern European perspective on spatial and temporal scaling issues in tundra ecosystems.

Methods:

Fieldwork is being carried out on sub-Arctic tundra ca. 7 km from the Swedish Royal Academy of Science Abisko Scientific Research Station, Sweden (68°21'N, 18°49'E). We are partitioning ‘field-scale’ measurements of net fluxes across the landscape, made by an eddy flux tower, into components relating to the elements of the tundra mosaic by means of series of plot-scale measurements of trace gas fluxes. These measurements sample the fine-scale mosaic across the landscape and through time, in terms of hydrology and soil processes. We are also attempting to predict trace gas fluxes both spatially across the landscape and temporally through the seasons in terms of contributions from identified soil-vegetation-hydrology associations within particular parts of the landscape mosaic.

Plot-scale measurements within specific components of the landscape mosaic, outside the footprint of the eddy flux tower, include a series of manipulations of winter/late spring snow cover. Snow fences are being used to increase snow depth and duration, and early melt of snow to alter growing season length of the tundra vegetation. Impacts of manipulations upon vegetation phenology and physiological development throughout the growing season are being monitored, along with impacts upon carbon turnover and partitioning (assessed by integrating canopy photosynthesis and ecosystem respiration measurements made using a ‘whole ecosystem’ cuvette). Soil organic matter mineralisation rates and major nutrient (N and P) fluxes are also being assessed, both during the thaw period and throughout the winter season.

To complement the above studies we are measuring snow distribution across the landscape including snow-pit surveys. Standard measurements of density, temperature, grain-size and type and wetness have been made. Much of the snow cover is highly wind packed, and has high densities as consequence. In areas where shrub communities dominate there are extensive regions of low-density depth hoar.

Two digital cameras have been sited overlooking the field site, recording two images a day to capture the large variation in snow cover as regular snow fall is redistributed by the wind and melts. These images are being ortho-corrected and used in conjunction with a high resolution DEM to generate snow covered area maps of the site (Fig. 3).

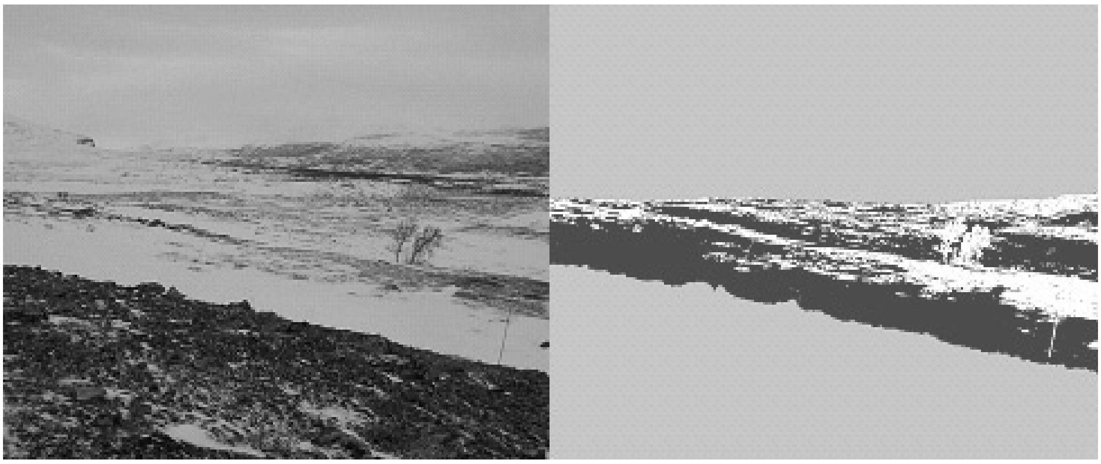

Figure 3. LEFT- example photograph of snow-lie (light) from automatic camera overlooking the research site. RIGHT- corresponding processed image of proportion of snow-lie (dark) on the landscape.

The hydrology of the study site is also being determined by a combination of measurement and modelling approaches. Measurements include the use of a grid of soil moisture determinations across a hill-slope, coupled with logging of water-table depth. Modelling approaches are being further developed at CEH Wallingford, utilising the MOSES model (Met Office Surface Exchange Scheme) - a comprehensive model describing energy, water and carbon exchanges between the land surface and the atmosphere.

The presentation will cover aspects integrating the key areas above with the aim of a better understanding of the key processes as we scale from plot to landscape responses of the soil-plant-atmosphere continuum of the Arctic tundra landscape mosaic.

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Responses of Tundra Ecosystems to Environmental Change: Observational and Experimental Results from the International Tundra Experiment (ITEX)

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Introduction

Evidence of environmental changes due to human-enhanced climate warming continues to accumulate from Polar Regions. However, the responses of tundra and taiga ecosystems to climate changes have been variable because of the wide range in process reaction rates, from metabolic processes to adjustments in ecosystem carbon balance, and the variability in environmental setting across local to regional scales. For example, relatively strong increases in rates of plant growth and changes in species composition and abundance have been observed in the Low Arctic, especially northern Alaska. However, very little change in tundra ecosystems has been measured in the High Arctic. These complexities in time and space scales make it difficult to predict trajectories of ecosystem change. It is also difficult to design field and modelling experiments to properly tease out answers to some of the questions that arise from the complexities. In addition, the basic responses to environmental variability and change are largely unknown for many northern systems, and differ because of initial conditions of the carbon and nutrient economy. In this presentation, I will examine some of the key scale issues and how studies along environmental gradients across the tundra biome will help to improve our ability to predict responses and feedbacks in these northern ecosystems to climate change. Results from the International Tundra Experiment (ITEX) will serve to illustrate the benefits of a multi-site approach to understanding the responses in these systems at local to regional scales.

Key Issues: scales and complexity

Arctic tundra ecosystems cover one fifth of the planet, and exist under a myriad of local and regional conditions. As Figure 1 illustrates, gradients in vegetation cover, soil carbon, and space vary (predictably) with latitude. Vegetation cover, and soil C and N contents decrease

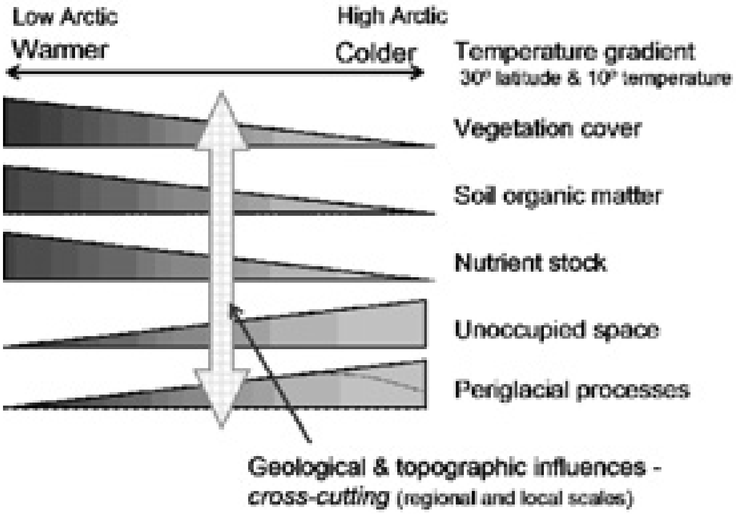

Figure 1. Latitudinal gradients in ecosystem characteristics. Local gradients imposed by geology and topography cut across these characteristics at specific sites.

and bare soil increases from low to high arctic systems. However, at the local scale there is considerable variability imposed by topography, geology, and other factors that cuts across and incorporates the latitudinal gradients. Soil moisture availability is an important factor influencing ecosystem characteristics at local scales. Components and processes respond to environmental changes at different rates: metabolic processes such as photosynthesis and respiration may respond in seconds to hours; allocation of nutrients and carbon within individual organisms may take hours to weeks; while changes in abundance and diversity of organisms through migration and genetics may take decades to centuries (Figure 2). Adding to this complexity are the multiple facets of environmental change linked to the changing climate. While warming is the best known of the drivers of environmental change, CO_2 fertilization, changes in UV radiation and increased atmospheric N deposition will have important and synergistic effects (Shaver et al., 2000). Clearly, there are no experimental approaches that can incorporate all of these temporal and spatial scales, appropriately. Ecosystem models provide tools to investigate potential effects of environmental change that incorporate processes at most scales, although the models themselves are based on the limitations of observational and experimental studies.

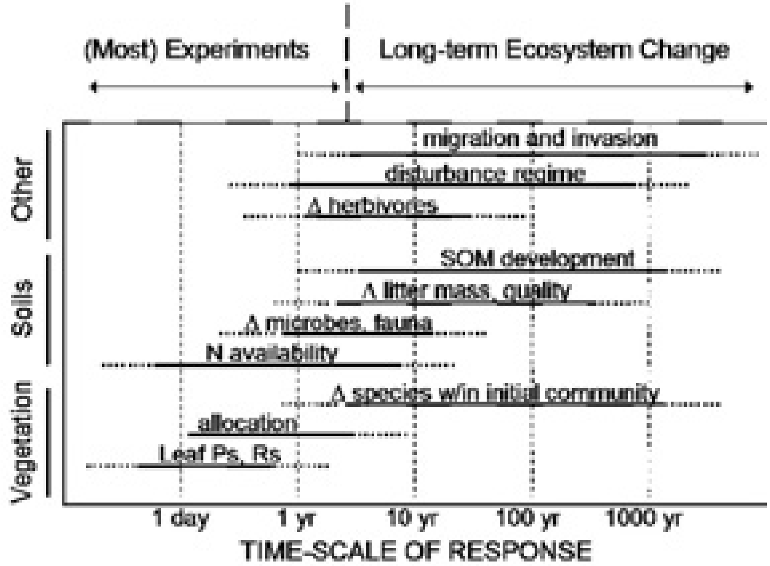

Figure 2. Response reaction times for various ecosystem processes (after Shaver et al. 2000).

Using gradients: observations from ITEX

Some of the limitations imposed by the complexities outlined above can be overcome by conducting experimental studies along environmental gradients where the long-term adjustments to processes with slow time-constants can be compared across ecosystem types. In addition, maintaining these studies over sufficient time periods to allow for adjustment in ecosystem conditions greatly increases the value of the results. These approaches are incorporated in the International Tundra Experiment (ITEX), where similar environmental manipulations have been maintained for >10 years at sites throughout the Arctic and in alpine tundra. ITEX sites span the biome (including alpine tundra), and studies at a number of site are conducted along local moisture gradients. Research at ITEX sites has focused on responses of individual plant species and of plant communities to experimental warming and annual climate variability (Henry, 1997; Arft et al., 1999; www.itex-science.net). Simple, passive warming devices (open top greenhouses) established at most sites, raise the temperature by 1-3 C during the growing season, but minimize the effects on precipitation and gas exchange. The temperature increases match the predictions of general circulation models for much of the Arctic.

Common methods at ITEX sites have allowed syntheses of results using meta-analysis that provide insight to variation in responses at different scales. Plant species found throughout the Arctic showed differential responses depending on geography and growth form. For example, low arctic species showed strong increases in growth, while those in high arctic sites had increased reproductive responses to warming (Table 1; Arft et al., 1999). Short-term growth responses were stronger in herbaceous than woody plants. However, these short-term, species level results could not predict the changes in composition and abundance at the community level. At the plant community level, cover (a proxy for biomass) and height of shrubs significantly increased in the warmed plots across the sites, whereas the cover of forbs has remained unchanged (Table 1). Cover of lichens and bryophytes was significantly reduced, likely due to shading. These changes occurred in just three years at some sites. These experimental results confirm observations of increased plant growth and shrub cover in low arctic areas of northern Alaska over the past two decades (Sturm et al. 2001; Serreze et al. 2000), but have also pointed to regional differences in responses. Shrub cover increased in the warmed plots at high arctic sites, although there have been no changes in the control plots. Much of the increase in cover and height is due to deciduous shrubs. Such a major change in the dominant functional group of these ecosystems (from low herbaceous to taller woody species) has important implications for feedbacks within the systems (e.g. increased wood and leaf litter, greater snow depth) and to the atmosphere (e.g. decreased albedo).

ITEX researchers have also used the long-term warming experiments to investigate ecosystem CO_2 flux responses across regional and local gradients, and have found important differences due to location and moisture conditions. In general, respiration is greatly increased by warming in the southern sites, leading to carbon losses, while a positive carbon balance is strengthened in northern sites; however, the responses vary in relation to soil moisture (Oberbauer et al., in prep) (Table 1). In addition, studies of soil nutrient dynamics have shown the warming experiments can greatly increase the availability of organic N, and stimulate microbial immobilization (Rolph et al., in prep.) (Table 1). Increased N availability will be required for the continued growth stimulation and will play a major role in how the

Table 1. Summary of results from ITEX research, based on responses to passive warming over 2-12 years.

Ecosystem component/process	**Important responses to experimental warming**
Plant species (Henry, 1997; Arft et al. 1999)	• Accelerated reproductive and vegetative phenology in nearly all species • Increased growth, especially in herbaceous species • Greater growth responses in low arctic sites • Greater reproductive responses in high arctic sites
Plant communities (Walker et al., submitted)	• Increased cover and height of shrub and graminoid species • Decreased cover of lichens and bryophytes • Decreased diversity
Net Ecosystem CO_2 Exchange (Oberbauer et al., in prep.)	• Increased ecosystem respiration • Increased carbon loss in low arctic sites • Variation in response due to moisture status • Strong annual variation in some sites • Greatest effects in moist and dry sites
Soil carbon & nutrient dynamics (Rolph et al., in prep.)	• Greatest changes in moist and wet sites • Increased availability of organic nitrogen • Increased nitrogen immobilization • Increased soil carbon concentration

carbon balance of these systems changes through time (e.g. Mack et al., 2004). Given that taiga and tundra ecosystems hold 20-25% of the soil carbon of global terrestrial ecosystems, it is critical that we understand the responses to environmental change in these systems in order to better forecast effects at all scales. Continued long-term research using coordinated networks such as ITEX will help to ensure that we capture important temporal and spatial variations in tundra ecosystem responses to climate variability and change. This will also help to improve modelling efforts to predict future response.

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Climatogenic Dynamics of Biota within the Current Distributions of Organisms and their Communities in the Arctic and their Implications for Response to Climate Change

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Many predictions on probable responses of Arctic plant cover to projected global climate changes can be made by studying biodiversity at a range of levels along differing scales of environmental gradients both within and between landscapes. Changes in biota composition and plant cover along latitudinal, longitudinal, altitudinal, inter- and intra-landscape gradients can be estimated without need for new investigations: there is enough information already available for this approach, but the data require analysis. This approach seems to be one of the most suitable in terms of time and the cost of new research, although monitoring from field sites that need to be established along environmental gradients is included in the approach.

Projections of vegetation zone shifts within the Arctic under expected climate warming can be determined from existing latitudinal gradients because the current pattern of species and community distribution along them reflect their dependence on macroclimate. It is a relatively easy task to estimate species diversity, spectra of life forms, plant functional types, geographical groups and other parameters of structure and composition of plant communities at any point on the gradient under known climatic conditions and then to compare the information with that from points south or north that are currently warmer or colder and represent future climate warming or cooling. It is also possible to estimate impacts of future changes in moisture conditions by analyzing current moisture gradients. There is sufficient information for this approach on vascular plants and vertebrates (mammals and birds), but less for cryptogamic plants, insects and soil invertebrates while changes in species number and distribution along latitudinal gradients are known only for restricted areas of the circumpolar Arctic.

The best studied area is Taymyr Peninsula (Siberia) that is the only location that offers a complete and continuous gradient from timberline to the polar desert and can be considered as a microcosm of the Arctic. The range of mean July air temperatures of 12ºC near tree line to 2ºC in the polar desert zone exceeds the expected increase in warming over the next 100 years along most of the gradient. Perhaps the main feature of the Arctic biota along this gradient is the sharp decrease in species diversity northwards of the timberline that takes place in all organisms but most noticeably in the advanced groups like vascular plants and birds than in the more primitive ones like cryptogams (lichens in particular) and soil invertebrates. However, the first response to climate change will be changes in species abundance and their within-landscape distribution. A careful study of species and plant community diversity and distribution along toposequences (from fell-fields to snow beds, from south to north facing slopes, from dry hill and hummock tops to wet depressions, from silt landslides to sand screes) can predict impacts that will occur in response to natural or man-made changes in climate. Such studies can assess the consequences of changes in biodiversity in the Arctic, as well as the causes.

The most suitable system for assessing quantitative (number of species and their abundance) and qualitative (species and plant functional type composition, spectra of geographical elements) changes over time in response to climate change is zonal vegetation that best corresponds to macroclimate. A good modeling object for this purpose is the plant association Carici arctisibiricae-Hylocomietum alaskani Matveyeva 1994. This is distributed throughout the tundra zone on Taymyr and is represented by longitudinal vicariants or vicarious associations in other territories of the Arctic. Its three well recognized latitudinal vicariants are connected with three tundra subzones. They have similar vegetation structure, physiognomy, dominants, and many common constant species but there are differences in their total species composition and abundance connected with species re-distribution within the landscape from one sub-zone to another. Along a south-north gradient, some species disappear, whereas some remain in the plant association. However, many of those that remain change their ecological range and move into intrazonal habitats. Similar changes occur in other associations in various environments like south-facing slopes, snow beds and wetlands.

Although the information at the species diversity level is relatively rich (however is far from to be complete for many groups), information at the community level is much worse and biodiversity at this level is unknown. There is not even a list of the community types (associations) in the Arctic, and even the most common community types are not well described throughout the whole range of their distributions. However, the study of the diversity of syntaxa is an aspect of circumpolar Arctic terrestrial biodiversity equally as important as existing studies that are creating pan-Arctic check-lists of different plant groups. Also, the detailed investigations on plant physiology, gas flux, measurements, net primary productivity, ITEX and other experiments have been undertaken in few sites, and within these few sites, only in a few types of vegetation. The information from these studies are not representative of the variation expected throughout the Arctic. In order to model, and generalize to the whole Arctic from the often important data arising from these studies, it is necessary to determine the distributional areas and structural variations in all published syntaxa and to recognize the position of each plant community type in a system of Arctic syntaxa.

We can predict but we cannot prevent the future changes in the Arctic. Facing these changes, we should study existing biodiversity and its differentiation along broad and small-scale gradients. The resulting data and understanding will contribute to parameterization of ecosystem function models, the testing of ecological theory, the restoration of ecologically damaged areas, and other fundamental challenges.

Important relevant literature

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Integrated Carbon Balance Studies for European Arctic Catchments

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Introduction

Carbon pools and fluxes were measured in two study areas in the European Arctic, the Usa Basin in Komi/Nenets (Russia) and the Teno Basin in Lapland (Finland) and Finnmark (Norway). Carbon pools were measured in phytomass and soil, and upscaled using GIS-based regional land cover and soil classification schemes (Kuhry et al., 2002; Kuhry and Virtanen, 2002; Mazhitova et al., 2003; Virtanen et al., 2004). Forest line location in GIS-based land cover classifications was modelled in relation to topography, regional climate (Christensen and Kuhry, 2000), permafrost distribution (Oberman and Mazhitova, 2003) and/or a landscape wetness index (see Virtanen et al., in press; Mikkola and Virtanen, submitted). Land/atmosphere carbon fluxes were conducted using chamber techniques (CO_2 and CH_4) in a variety of land functional types in the tundra (Heikkinen et al., 2002a/b, 2004) and using tower measurements (CO_2) in a mixed spruce forest in the northern taiga (Bobkova et al., unpublished data). Changes in river discharge of the Usa River and two of its tributaries in relation to regional climate, vegetation and permafrost dynamics were modelled with a GIS-based hydrological model (van der Linden et al., 2003). Runoff and water chemistry (TOC) were measured in a number of subcatchments (Huitu and Arvola, 2003, unpublished data). Results from many of these studies have been published for the Usa Basin, and, to a lesser extent, for the Teno Basin. At present, the results from these separate components are being combined into integrated carbon balance assessments for both regions. First results will be available for the Usa Basin, based on flux studies conducted in the year 2001.

Study Areas

The location of the Usa and Teno Basins, investigated subcatchments (Khosedayu, Utsjoki) and carbon flux study sites (Lek Vorkuta, Zelenoborsk) are indicated in Figure 1. The Usa Basin is mostly lowland, 30% forested, with isolated to continuous permafrost. The forest line, formed by spruce, follows approximately 67º N latitude. The Teno Basin is an area of valleys, low mountains and upland plateaus, 40% forested, with only isolated patches of permafrost. The mountain birch forest limit is located between ca. 250-350 m altitude.

Methods

Regional integration of the different component studies in the Usa Basin is achieved through a combination of approaches, including past analogues, geographic analogues, monitoring, process studies, GIS and modelling. The integration is facilitated by the choice of a common study area, the implementation of a regional GIS and the application of the same climate change scenarios.

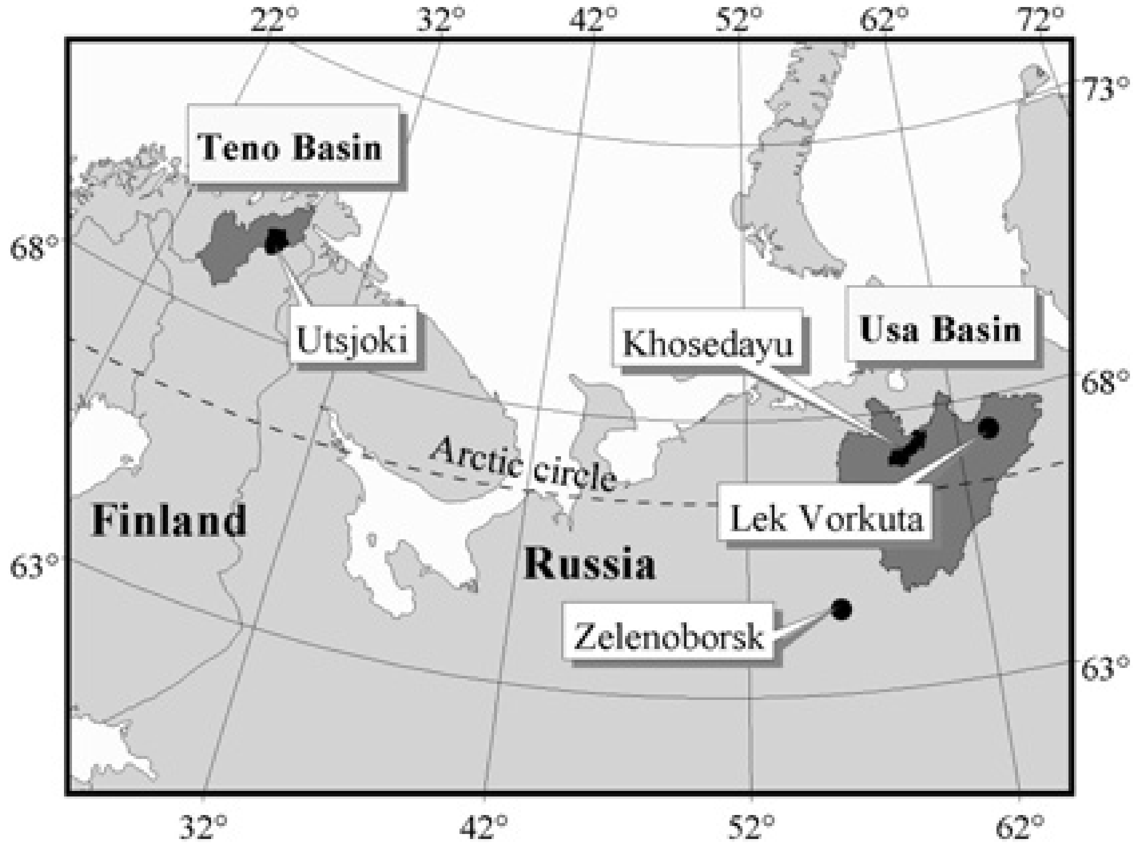

Figure 1. Location of study areas and sites in the European Arctic.

The following GIS layers are available for the Usa Basin:

- Regional topography, with a derived landscape wetness index
- Regional hydrology, with discharge measurements from river stations
- Regional climate model, validated with meteorological data from climate stations
- Regional land cover classification, with ground truth plots and phytomass measurements
- Regional soil classification, with pedon descriptions and soil carbon measurements
- Regional permafrost map, with landscape features and borehole data

Carbon flux studies in or near the Usa Basin were carried during the growing season, with some winter time measurements. The year 2001 is the period with a nearly complete overlap of flux studies. The techniques, localities, and time period of monitoring were (for location see Figure 1):

- Chamber measurements in the southern tundra at Lek Vorkuta from all surface functional types, except willow (1999 and 2001)
- Tower measurements in the northern taiga near Zelenoborsk in the dominant mixed spruce forest (2001-2002)
- River runoff and TOC estimates in the tundra from the Khosedayu River (1998-2002), with some measurements in the Lek Vorkuta River
- (No local measurements in taiga wetlands, lakes and rivers)

Carbon pools and fluxes were upscaled using GIS-based regional land cover and soil classification schemes. Climate change scenarios for 2080 (transient +2.8 °C) and 2230+

(equilibrium + 4.1 °C) were obtained from the HadCM2S750 integration (Hadley Centre, Bracknell, UK) through the Climate Impacts LINK Project (Climatic Research Unit, University of East Anglia, Norwich, UK).

Results and Discussion

Preliminary calculations based on available flux studies complemented with published data indicate that the Usa Basin was near carbon neutral (2 gC m^{-2} yr^{-1} sink; range -4 to +8 gC m^{-2} yr^{-1}) in the relatively warm and dry year 2001 (losses from tundra and rivers, gains in wetlands and taiga). In the colder and moister year 1999 the area was most likely a carbon sink (no net loss from tundra).

The extensive data set on land functional types with associated flux measurements and phytomass and soil carbon estimates permits a sensitivity analysis of the Usa Basin carbon balance to future global warming using analogue and modelling approaches. Results will be presented that compare the impacts of changes in different landscape components, including forest growth/migration vs tundra soil organic matter decay, forest growth/migration vs thermokarst erosion and forest growth/migration vs paludification. The important difference between a transient 'disturbance' response and a new 'equilibrium' condition will be discussed.

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Effects on the Carbon Balance of High-Arctic Tundra: Entire Growing Season Warming Versus Heat Wave Exposure

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Introduction

Besides the general warming, the IPCC climate scenarios also project extreme climate events (a.s. more hot days, heat waves) to increase in frequency during the next century (Houghton et al., 2001). Nevertheless, we are not aware of any research that investigates possible stress effects of extreme temperature events on the vulnerable arctic tundra. For this purpose, we exposed plots of tundra vegetation to both a small temperature increase (+ 2.5°C) during an entire growing season and to an experimental heat wave (+9°C during several days). To generate these increments we used the Free Air Temperature Increase-method, designed to homogeneously heat limited areas of short vegetation (Nijs et al., 1996; Nijs et al., 2000), while previous research mostly used greenhouses or open top chambers (Dormann and Woodin, 2002). Our first objective was to detect possible changes or stress caused by warming. A second objective was to assess whether warming influenced the carbon exchange rates (i) uptake of CO_2 by photosynthesis, (ii) loss of CO_2 by below ground respiration and (iii) loss of CO_2 by canopy respiration. Because tundra ecosystems constitute large stocks of carbon (Schlesinger, 1984), they can, when warming releases carbon, attend a positive feedback and stimulate climate change. Otherwise carbon uptake can retard this effect.

Material and Methods

The study site is located in the vicinity of the Zackenberg research station on the Northeast coast of Greenland (74°28'N, 20°34'W, 25-m elevation). We selected six similar tundra plots (40 x 50 cm) with *Salix arctica* Pall., *Arctagrostis latifolia* Griseb., *Carex bigelowii* Torr. ex Schwein and *Polygonum viviparum* L. as dominants, and we estimated living plant cover. Then, we appointed the plots to two treatment groups (each 3 plots) to have approximately similar cover and species composition in both. In 1999, temperature was increased with 2.5°C during the entire growing season (from the end of June till the end of August). From 14 July to 22 July 2001, we increased temperature for 13 days with 9°C, the maximum reach of the equipment, to simulate a heat wave. Each time three plots (one group) were continuously heated with infrared radiation (0.8 – 3 µm) from FATI-units (two 1500-W sources in a waterproof housing on a tripod). The surface temperature of the vegetation, soil temperature at 2.5, 7.5, 15 and 30 cm depth, air temperature at 5 cm height and photosynthetically active radiation (*PAR*) were measured with sensors and recorded with data loggers every 30 minutes. We measured soil volumetric water content, thawing depth, green cover, species composition, growth rate, chlorophyll content and chlorophyll fluorescence. Gross photosynthesis (P_{gross}), below ground respiration (R_{soil}) and canopy respiration (R_{canopy}) were regularly determined with closed dynamic CO_2 exchange systems, and the whole-growing season C-balance was reconstructed by relating these components to potentially controlling factors.

Results and conclusions

During the entire growing season warming, thawing depth and green cover increased in heated plots, while soil moisture was not significantly affected. P_{gross} increased 24.2%, owing to both a green cover and a physiological influence of warming. Below ground respiration was enhanced 33.3%, mainly through direct warming impact and in spite of lower Q_{10} in the heated plots; the factors controlling R_{soil} were day of the year and soil moisture. R_{canopy} did not differ significantly between treatments, although green cover was higher in the heated plots. This tundra ecosystem acted as a relatively small net sink both under current (0.86 mol CO_2 m^{-2}) and heated (1.24 mol CO_2 m^{-2}) conditions (Figure 1A). Nevertheless, turnover increased, which was best explained by a combination of direct and indirect temperature effects, and delayed senescence (Marchand et al., unpublished).

During exposure to the experimental heat wave, leaf growth rates of *Arctagrostis latifolia* and *Carex bigelowii* were increased. Furthermore, increased green cover and higher chlorophyll concentrations of all four dominant species at the end of this heat wave, are also indications of vegetative growth stimulation. Another confirmation for improved plant conditions during the heat wave, was a higher photochemical efficiency (F_v/F_m) and photosynthesis of plants in heated plots compared to plants in unheated plots (Figure 2). Nevertheless, during the period after the heat wave, heated plants were more stressed than unheated plants, probably because they were exposed to lower ambient conditions to which they could not acclimatize. In spite of that, photosynthesis was still slightly enhanced in this period, which indicates indirect effects of warming. In addition, the reconstruction of the carbon balance by its three components (photosynthesis, soil and canopy respiration), revealed that soil respiration and canopy respiration were stimulated by the instantaneous warmer soil and vegetation, respectively (Figure 1B). Thus, during the heat wave, the heated ecosystem was a smaller sink compared to the unheated ecosystem. This indicates that, if more heat waves will occur in the future, this ecosystem may become a source and stimulate climate change by a positive feedback.

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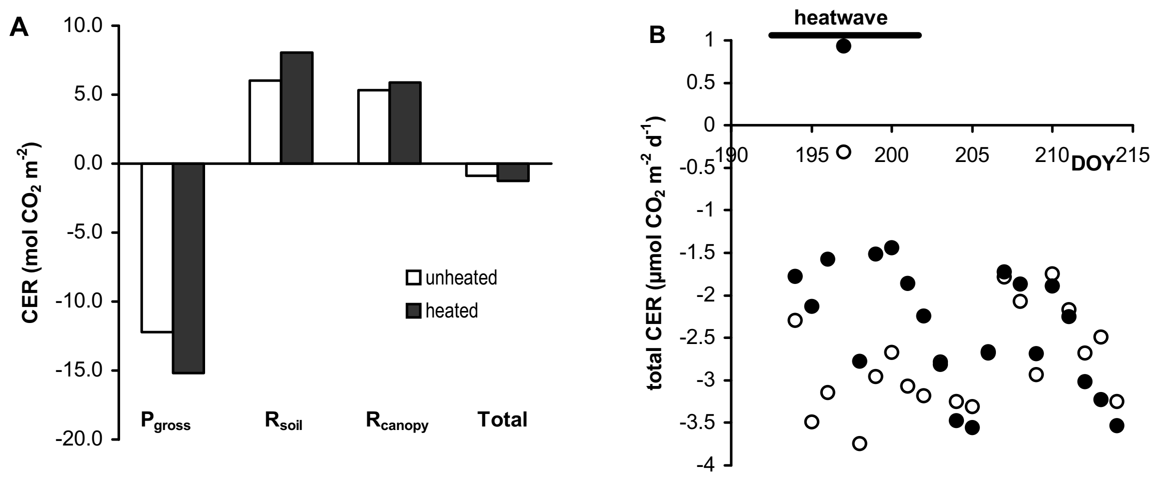

Figure 1. (A) Cumulated CO_2 exchange rate (CER) over the entire growing season of 1999, separated by the three components: photosynthesis (P_{gross}), soil respiration (R_{soil}) and canopy respiration (R_{canopy}). (B) Reconstructed time course of daily total net $CER_{ecosystem}$ during the 2001 heat-wave experiment. Values are averages for the three control plots (open symbols or bars) and the three heated plots (filled symbols or bars). Positive values are CO_2 release. DOY: day of the year.

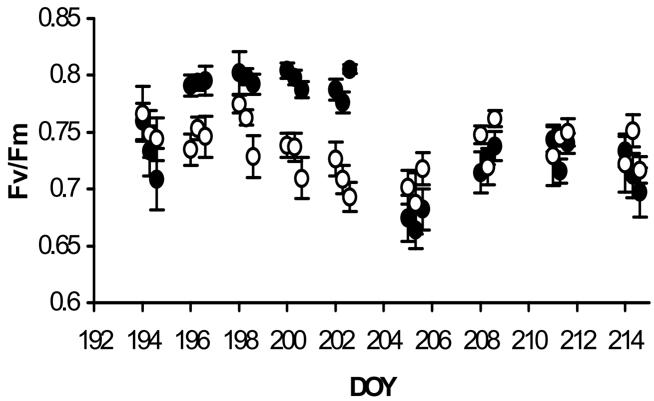

Figure 2. Time course of photochemical efficiency (F_v/F_m) of *Salix arctica*. Averages ± 1 SE of 15 plants per species of both heated (●) and unheated (❍) treatment (5 per plot). Each measurement day (DOY) has a morning (9h00), noon (13h00) and evening (18h00) measurement.

Land Surface Radiation Budget Response to Global Warming: Case Study for European and Asian Radiometric Network

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Introduction

The land surface albedo is a key parameter influencing the climate near the ground. Forecasting the Earth climate for the next few decades is indeed a great concern of the mankind since it yields severe implications for delineating the future human being, preserving the biodiversity, enhancing the renewable resources, and restricting the hazardous events. A geographic reallocation of the terrestrial climates is even seriously envisaged for the future. The climatic system was originally rhythm by the time duration of the summer season. However, the enhanced anthropogenic pressure seems to have modified the environmental mechanisms in perturbing the atmospheric fields, namely the air temperature and the rainfall distribution. Owing to strong feedbacks effects, the role of the sun as an energy source is still fundamental for determining the weather at the atmospheric boundary layer (Noilhan, and Planton, 1989). In particular, the determination of a surface albedo, that is the ratio of incoming to reflected solar radiation, is mandatory (Sellers, et al, 1986). The albedo quantifies the proportion of absorbed energy that can be later transformed, in a more or less straight mode, into the heat and latent fluxes (Ross, 1981). It accounts for eight percent of Earth radiation budget. Therefore, it must be determined with a sufficient accuracy (Pokrovsky, and Roujean, 2002a,b). High latitude area proved to be extremely sensitive to recent climate change. Therefore, main attention in this study was drawn to high latitude stations located in the East and West Siberia.

Datasets

The twenty years (1976-1995) monthly data of 12 representative radiometric stations located in European and in Asian parts of Russia were used in this study (Pokrovsky, and Makhotkina, 2002). Hourly global, diffuse, direct and reflecting radiation data were digitized and checked. Short wave radiation budget (RB) data were also available in this study. Simultaneous meteorological parameters (air temperature and humidity, precipitation amount, wind velocity and direction, soil temperature/moisture at surface and 5, 10, 15 cm depths) were provided at the same sites. Cross-correlation features were investigated and physical explanation of found trends in the RB components was provided.

Method

Along with linear tend computations we carried out alternative studies of time series (quadratic, cubic and non-liner approximations). All mentioned approaches with the exception of non-linear trend technique are known and widely used. Therefore, we consider non-linear technique (Pokrovsky, et al, 2004). Let us assume that $x_1,...,x_n$ is an input time series. Our task is to recover it from short-term disturbances and to reveal non-linear long-term components. We transform input data $x_i\,(i=1,...,n)$ to smooth values $\hat{x}_i\,(i=1,...,n)$ in accordance to formula: $\hat{x}_i = \sum_{k=1}^{n} \rho_{ik} x_k$. The set of the weight coefficients $\rho_{ik}\,(i,k = 1,...,n)$ should be determined from following relationships:

$$\sum_{k=1}^{n} \rho_{ik} = 1, (i = 1,..k)\,;\; \sum_{\substack{k=1;\\ k\neq i}}^{n} \rho_{ik} = \alpha\rho_{ii}, (i = 1,..k), (0 \le \alpha \le 1)\,;\; \rho_{ik} = 1/(i-k)^2\,(i,k = 1,...,n; i \ne k)\,.$$

Thus smoothing estimate $\hat{x}_i\,(i = 1,...,n)$ is obtained from all input data, but with different weights. Smoothing coefficient α regulate smoothing rate. When α=0, smoothing is absent. Smoothing rate is maximal when a =1. Figure 1 demonstrates that this trend technique provides the most reliable trend results when compare with other approaches.

Results

An analysis of linear and short-term nonlinear trends for land surface albedo and radiation budget components has been carried out. Linear trend investigation showed that albedo, reflected and global radiation fluxes increase in summer, while radiation budget decrease at most continental sites. More rapid increasing of reflected radiation is a reason of negative trend in radiation budget time series. We demonstrated that reflected radiation time series is coherent with air temperature and precipitation time series. We suppose that temperature increasing and precipitation decreasing (fig.2) are main factor of soil and grass dryness, which is a reason of albedo dropping in hot period of year. In contrast, the global and reflected radiation fluxes decrease at North-East Asia and North-West European regions, which are greatly impacted by growing cyclonic activity. We showed that positive trend in precipitation in these areas might be a cause of more rapid decreasing in global radiation then in reflected radiation because of positive trend in air and soil temperature, which accelerate an evaporation process at land surface. Latter phenomenon is a cause of negative trend in radiation budget time series for both: continental and non-continental stations at summer season. In winter seasons we found out inverse tendency. Albedo and reflected radiation time series have negative trends, while those for global radiation have positive trends. Hence, radiation budget time series has a positive tendency for most continental stations. Snow cover reflection properties depend on roughness and wetness of snow. The roughness of fresh snow is higher than those of old snow cover. Therefore, a positive trend in precipitation time series revealed at most sites might explain albedo dropping. Wetness of snow is depended on air temperature. Positive air temperature trend delivers another factor of albedo decreasing in winter season. So, radiation budget decreases in summer and increase in winter. But annual total effect is negative. Therefore, this feedback mechanism might be considered as negative and compensation loop to global warming of Earth climate system.

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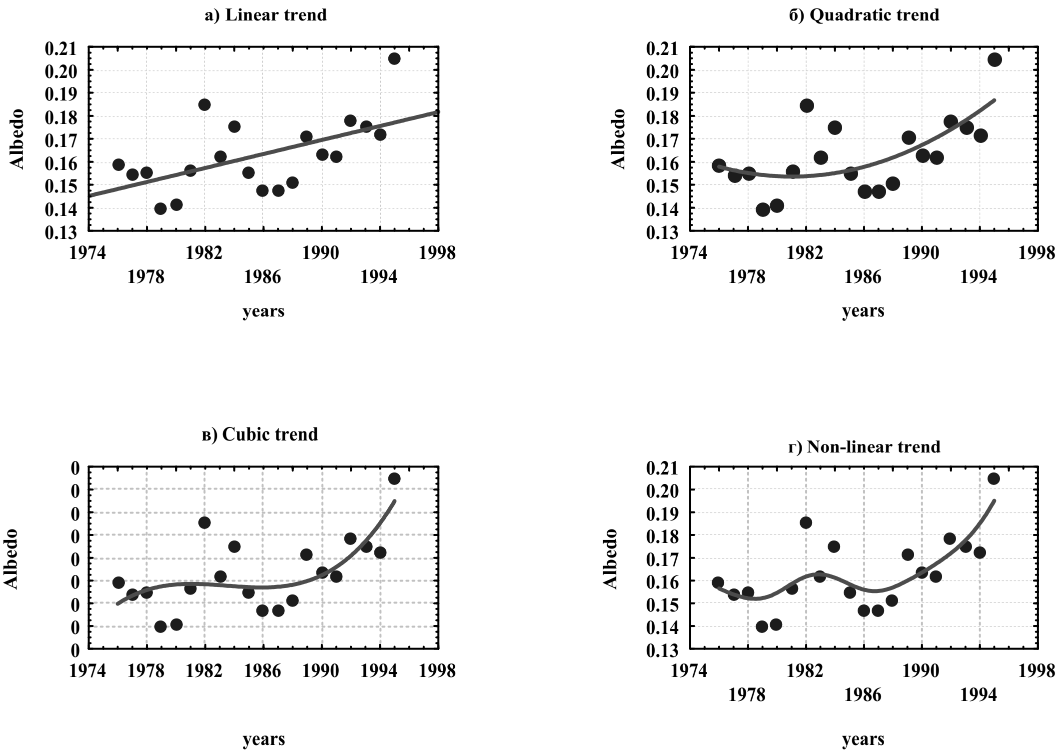
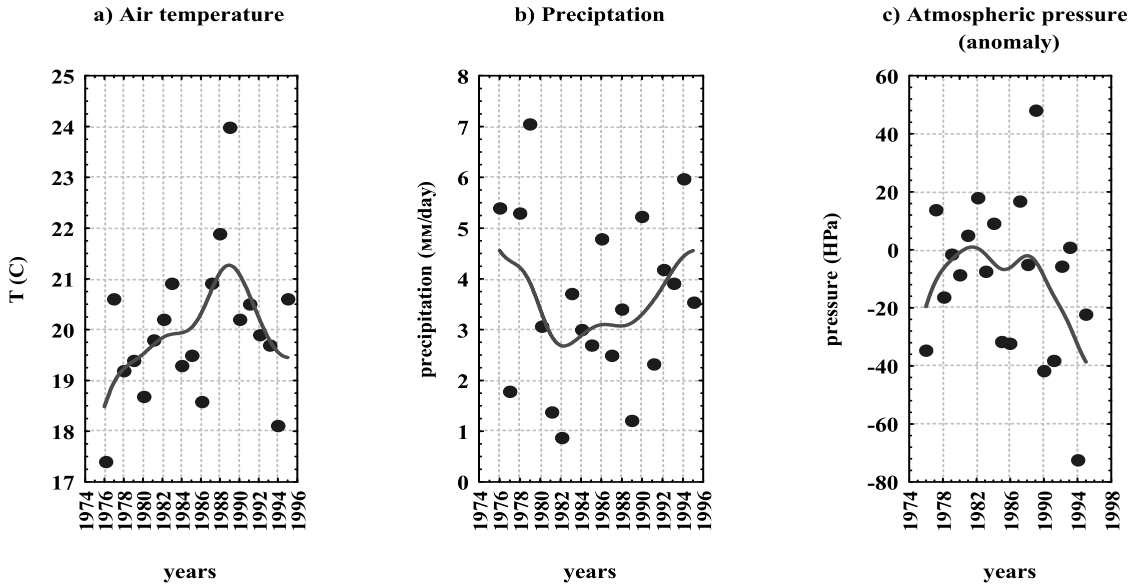


Albedo trends: Irkutsk, July

Figure 1. Comparison of various trend approximation techniques.



Meteorological parameter time series: Omsk, July

Figure 2. Relationship between series of major meteorological parameters.

Possible Feedbacks on Arctic Cloud Formation: Can the Arctic Biosphere Affect the Melting of the Ice?

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Introduction

Clouds have a profound impact on the radiation budget of the Earth and calculations show that small changes in cloud cover or optical thickness may offset – or double - even at a doubling of greenhouse gas concentrations. In contrast to the mid-latitude oceans, low-level clouds are a warming factor in the central Arctic through most of the year. In winter the effects of low-level clouds are the single most important local factor determining the stability of the lower troposphere. In summer, with frequent low clouds, changes in their microphysics can alter their reflectivity for solar radiation as well as cloud lifetimes. These processes are very poorly described in current climate models and because of the potential for a large effect, it is essential that we should understand the sources, nature and controls on the supply of cloud droplets.

Formation of clouds requires the presence of small airborne aerosol (particles), so called cloud condensation nuclei (CCN). While the amount of condensed water in a cloud is determined by thermodynamic and dynamic properties, the number of droplets is regulated by the abundance of CCN. With many CCN, the condensed water is distributed over many small droplets rather than over a few large. This in turns makes the cloud look "whiter", thus reflecting more solar radiation back to space. This is known as the "indirect effect" of particles on climate.

The well-known hypothesis of *Charlson et al*. (1987) proposed one biological influence on radiation and climate based on the indirect effect of aerosols. The gas dimethyl sulfide (DMS), produced by marine phytoplankton, is oxidized in the atmosphere to sulfuric acid, nucleating particles that grew to become CCN. It was suggested that climate change would change DMS production to form a negative feedback through its effects on CCN.

Sulfate-containing aerosols are ubiquitous in the atmosphere and usually the most numerous particles capable of acting as CCN, so that the theory seems reasonable. But does DMS alone control the number of CCN or could there be other biological controls on CCN formation in marine air remote from land sources? The central Arctic Ocean in summer provides an ideal laboratory for studying that question. Excursions of continental and most likely polluted air into the basin are infrequent, and low cloud and fog at the fringes of the pack ice rapidly remove aerosols. A shallow boundary layer capped with a temperature inversion limit mixing from above the clouds (*Tjermström et al.,* 2004), where long-range transported aerosols from distant sources may reside.

Cloud Forming Particles over the Pack Ice

An expedition in 1991 (*Leck et al*.,1996) revealed strong summer sources of DMS near the ice edge and adjacent waters and the dominant sulfate and methane sulfonate ions in the accumulation mode (diameters 100 to 1000 nm) aerosol (*Leck and Persson, 1996a,b*).

However, as these particles become CCN while traveling in over the pack ice, they become parts of clouds droplets that eventually deposits at the surface and are lost forever. The number of CCN with a source at the ice edge thus decreases with time of transport away from the ice edge. This has a profound impact on the properties of Arctic clouds, making them “grayer” than their mid-latitude counterparts.

Can climate change alter the Arctic system such that more biogenic particles are produced locally by generating larger areas of open water in the pack ice? Are there already other processes that produce biogenic aerosols in the pack ice? Will an enhanced production of CCN in the central Arctic Ocean act as a negative feedback, producing brighter clouds reflecting more solar radiation back to space?

To help answering these questions, Arctic Ocean summer Experiments were launched the same area north of 80°N, in 1996 (*Leck et al., 2001*) and 2001 (*Leck et al., 2004*) on the Swedish icebreaker *Oden*. We found clear evidence that local aerosol production at the ocean surface occurred even when the fraction of ice was large (~ 95%). These novel conclusions were based on *in situ* measurements of atmospheric aerosols, boundary-layer structure, and of the film on the surface of the open leads, the “surface microlayer of the open leads” (SMOL).

A radio-controlled miniature boat was used to collect the <100 μm thick surface film of the open water between ice floes (*Knulst et al.*, 2003), and the water from the collected film was examined. Aerosol particles were simultaneously collected from the atmosphere. Similarity in morphology, chemical and physical properties of the numerous aggregates and their building blocks, and of bacteria and other micro-organisms was found in both the air and water. This strongly suggests that the airborne particles were ejected from the water by bursting bubbles (*Bigg et al*., 2004*; Leck and Bigg*, 2004).

On average during the five weeks spent in the pack ice region during 2001, SMOL-derived particles represented more than one-third of the collected airborne particles; more than two-thirds on sunny days. Instead of being liquid sulfuric acid, these particles were water insoluble, often having a crystalline appearance, either as aggregates or individuals (*Leck and Bigg,* 1999), Figure 1. This invalidates the hypothesis that DMS oxidation products alone produces particles of this size (*Charlson et al*.,1987).

One feature of SMOL particles was that they were joined together and surrounded by a diffuse electron-transparent material. Close examination of airborne particles revealed its presence on them as well. Examples are shown in Figure 1. The gel-like secretions of microalgae and bacteria known as “exopolymer secretions” (EPS) are well known to marine biologists, but not to aerosol scientists. EPS consists mainly of polysaccharides and has a number of properties (*Decho*, 1990). The molecules are highly surface-active, take up water like a sponge and release it very reluctantly. They capture heavy metal ions and readily bind other molecules, large and small, into their structures and spontaneously assemble into gels. The gels collapse under the influence of ultraviolet light and acidification (*Chin et al.* 1998). Their lifetime in the atmosphere is therefore limited and the collapse of the structure having such strong water retentive properties explains some of the puzzling features of the aerosols observed over the pack ice. For example the expulsion of water as the gel collapses may explain why airborne aggregates and bacteria very rarely have attached sea salt. The breakup of aggregates when the joining EPS gel collapses is also a sufficient reason why the airborne aggregate size distribution so closely resembles that of the SMOL aggregates but is shifted to a smaller size. Comparison of the size distribution of airborne aggregates and particles with the size distribution of the total aerosol provided by a differential mobility sizing system strongly suggests that broken aggregates provide almost all the particles between 10 and 70nm diameter, the Aitken mode.

Implications of a Local Pack Ice Source of Cloud Forming Particles

Fresh aggregates with gel on them could act as CCN directly because of the gel's strong surface active properties. Aqueous oxidation of sulfur dioxide could then produce sulfur-containing particles with aggregates inside. Those that have lost their gel could still act as sites for the condensation of the oxidation products of DMS, and so could also lead to production of sulfur-containing aerosols. DMS concentration will determine the mass of sulfate produced but will have only a minor influence on the number of CCN and thus cloud droplets, which will be dictated by the number of airborne particles originating in the SMOL.

Boundary layer clouds are frequent in the summer Arctic, are optically thin and have low concentrations of CCN, compared to boundary-layer clouds at lower latitudes. These are conditions that maximize effects of changes in CCN and cloud droplets on short-wave radiation. On a regional scale there is therefore a potential for a biological impact on climate, but the emphasis has shifted from phytoplankton beyond the ice edge to bacteria and microalgae, and their secretions, within the pack ice. While there can at present be no definite answer to the question in the title, it does look to be a tentative "yes", and the marine biosphere will affect the melting of the ice.

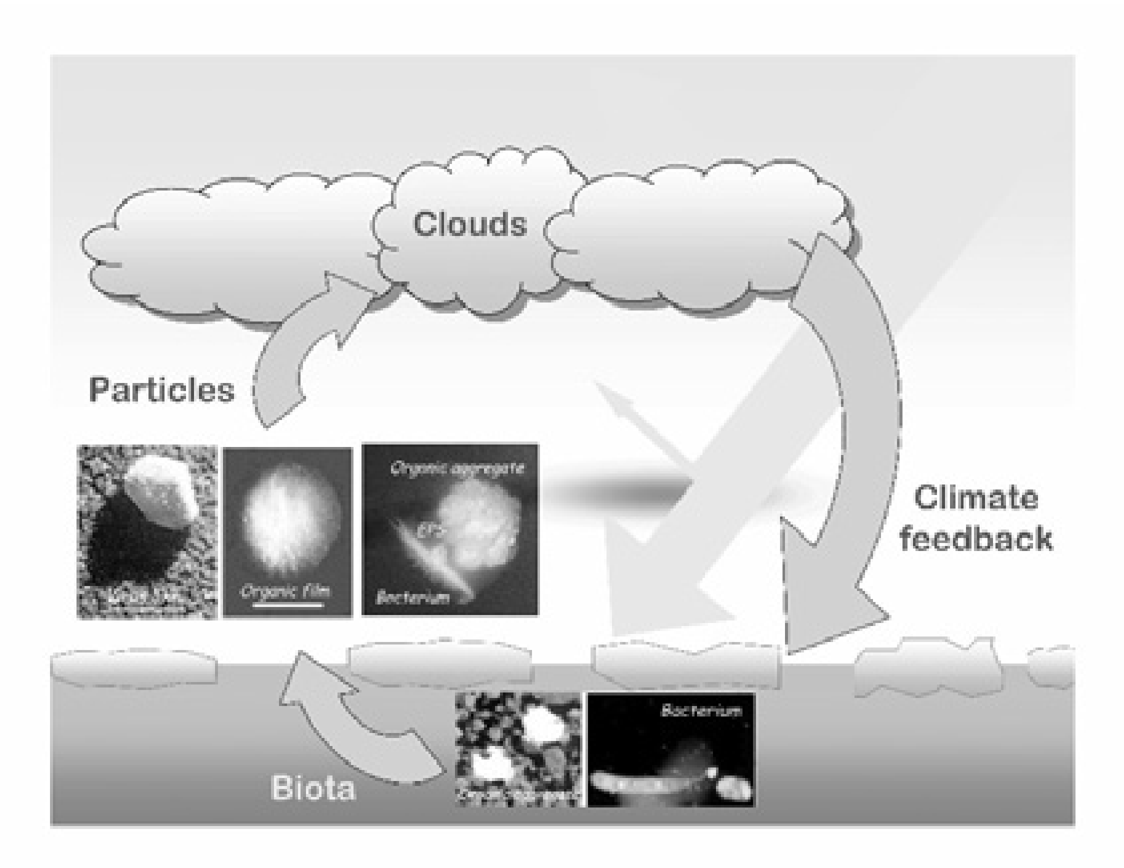

Figure 1. A simplified picture of the relationships between the processes described and how they are connected to cloud–aerosol interactions.

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How Good is the Surface Energy Balance in Current Atmospheric Climate Models?

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1. Introduction

Climate forcing, as well as the drivers of climate change, are parameterized in all climate models. There is a controversy within climate modeling, if the so called "model physics" has anything to do with actual physics or if it is just a package of tunable statistic relationships of a more obscure nature. Given how climate is generated in a climate model, it is exceedingly clear to us that unless the "model physics" at least attempt to mimic the actual physics, climate modeling is not meaningful.

Arctic is more sensitive to climate change than other regions. On average in 19 CMIP (Meehl et al. 2000) climate-change simulations, the Arctic warms 2.5 times the global average warming (Räisänen 2001). We see today signs that global warming has started to impact the Arctic (Serreze et al. 2000, Comiso 2002). Still, the inter-model spread in the CMIP ensemble is by far the largest in the Arctic (Räisänen 2001) and current GCM have problems reproducing today's Arctic climate (Walsh et al. 2002).

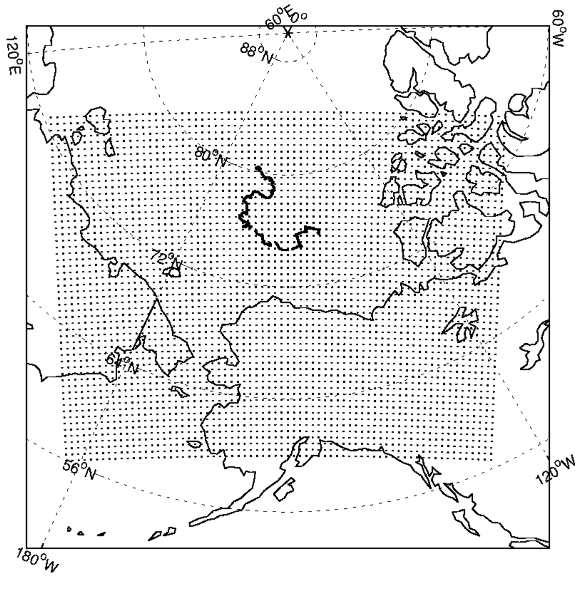

Figure 1. The ARCMIP exp. #1 model domain.

The large climate sensitivity of the Arctic is due to strong feedback mechanisms, the ice/snow-albedo feedback probably being the strongest. An adequate description of the fluxes of heat and momentum at the ice surface lay at the heart of a proper representation of this feedback. An evaluation of surface fluxes has been difficult due to lack of adequate data. The Surface Heat Budget of the Arctic Ocean (SHEBA, Uttal et al. 2002) experiment now makes this possible.

The aim of the Arctic Regional Climate Model Intercomparison (ARCMIP, Curry and Lynch 2002) project is to improve climate models for the Arctic, by comparing models to each other and to SHEBA data. In this experiment all models were set up on a common domain with the same resolution, centered on the SHEBA ice-drift track (Fig. 1). All six models (see acronyms in Fig. 2) used the same 6-hourly lateral boundary conditions from operational ECMWF analyses. Sea and ice surface temperatures and ice fractions were prescribed from satellite observations. The models were run 13 months, from 1 September 1997. In this paper we focus on an evaluation of the surface fluxes and the boundary-layer vertical structure (Tjernström et al. (2004).

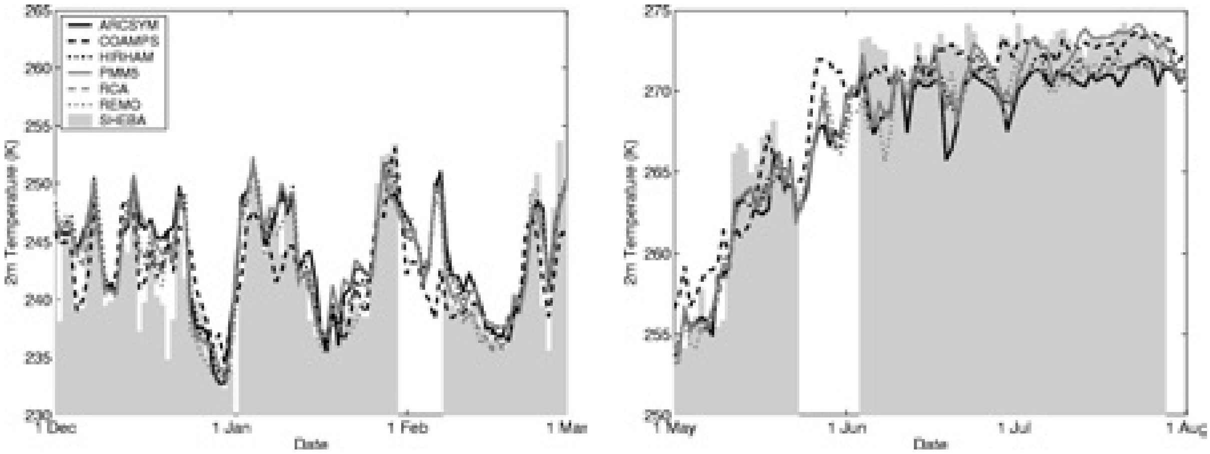

Figure 2. Siurnally averaged 2-meter air temperature during (left) winter and (right) summer for the different models and from SHEBA data, as indicated in the legend.

2. Results

In general the relatively small domain ensures that all models larger-scale dynamics adhere to that of the driving analyses, although smaller differences do occur (Rinke etal. 2004). Fig. 2 shows daily averaged 2-meter air temperature in all the models, for some winter and spring/ summer months. While the ice-surface temperature was prescribed, the models are expected to follow the observations closely. It is surprising to find some rather large differences between models and observations. During cold periods in December 1997, many models are ~ 10 ºC too warm, even as weekly averages. The coldest period, around 1 January 1998 is, however, well captured by all models. In summer, the differences are smaller, but with a systematic disparity between models close to ~ 0 ºC (the melt-point of fresh water) and others closer to ~ -1.8 ºC (the melt-point of ocean water).

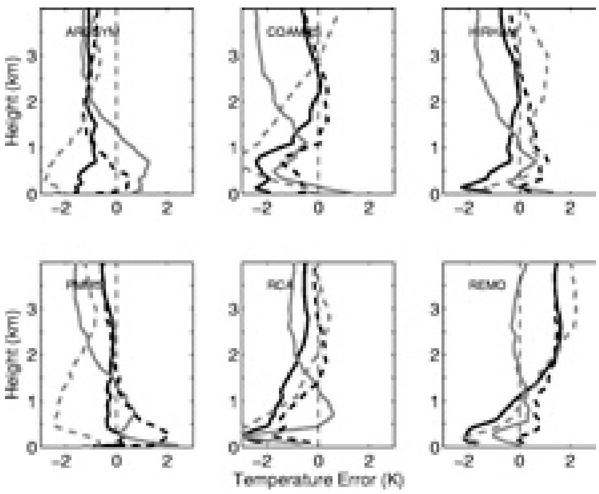

Figure 3. Seasonal averages of temperature bias profiles. Fall and winter are shown with solid, black and grey, and spring and summer by dashed, black and grey.

Seasonally averaged temperature bias profiles are shown in Fig. 3; two things are obvious. First, the biases are much larger and more variable below ~ 1 km. Second, different models behave very different also in the free troposphere. Larger biases closer to the surface indicate deficiencies in boundary-layer parameterizations, probably often related to formation of low-level clouds; note the summer low-level cold-bias in all models, presumably due to overestimated cloud-top cooling. Although all models should be constrained by the prescribed lateral boundary conditions in the free troposphere, the errors aloft are also significant, mostly as a cold bias. While some models have a consistent bias through the year, others are very variable from season to season.

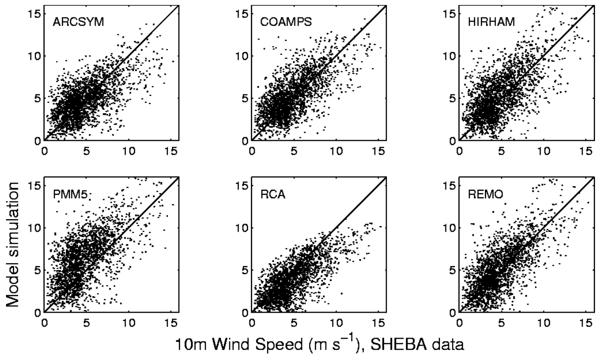

Figure 4 Scatter plot of the modeled 3 hourly wind speed compared to SHEBA measurements.

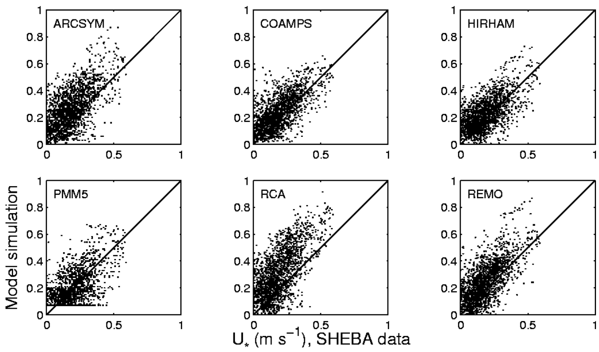

Figure 5. Scatter plot of the modeled 3 hourly friction velocity compared to SHEBA measurements

Near-surface wind speeds (Fig. 4) follow the observed variability well in all models, but with systematic biases in addition to the scatter. Annually averaged biases range from ~ -1 ms^{-1} in RCA to ~ 1.5 ms^{-1} in Polar-MM5. In some cases, this bias is consistent with similar biases in the momentum flux, expressed as friction velocity in Fig. 5, for example the high bias in RCA friction velocity is consistent with the low wind-speed bias.

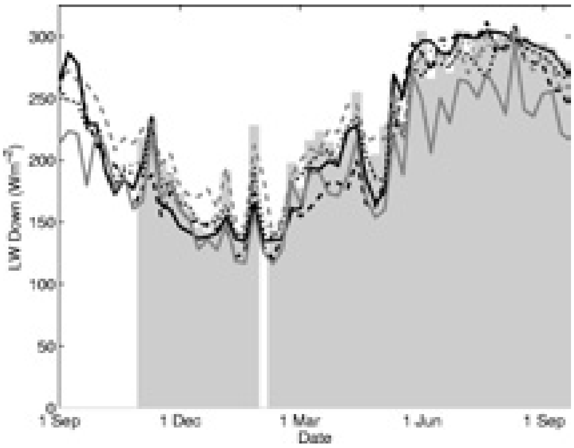

Figure 6. As Figure 2, but for weekly averaged down-welling long wave radiation.

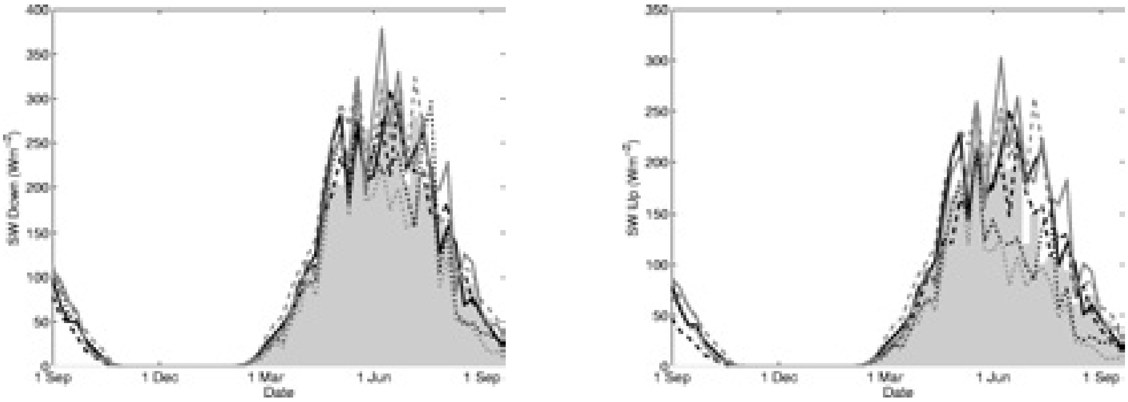

Figure 7. As Figure 2, but for weekly averaged (left) down-welling and (right) up-welling short wave radiation.

Given the difficulties to model clouds, the surface radiation fluxes are surprisingly accurate (Figs. 6-7). While some models do have biases ~ ± 20 Wm^{-2}, the correlation to the observations is high. Concerning turbulent heat fluxes the picture is distinctly more depresssing. All models fail badly (Fig. 8). Although the annual bias is small, the correlation to the observations is low. Annually accumulated heat flux errors are an order of magnitude.

3. Discussion

We believe that surface friction in these models was originally tuned against surface pressure to ensure reasonable development of synoptic systems, worrying less about the actual friction. Turbulence then “picks up the slack” from other unknown deficiencies in the models. Non-linear feedbacks between wind speed and turbulence then adjust to an unrealistic state, disrupting the turbulent heat fluxes. The results are superficially nice representations of Arctic climate, often for the wrong reason. If coupled to an ocean model with sea-ice, the result may instead be a very poor representation of current conditions. We will leave the consequences for the reliability of Arctic climate change simulations to the reader to ponder upon.

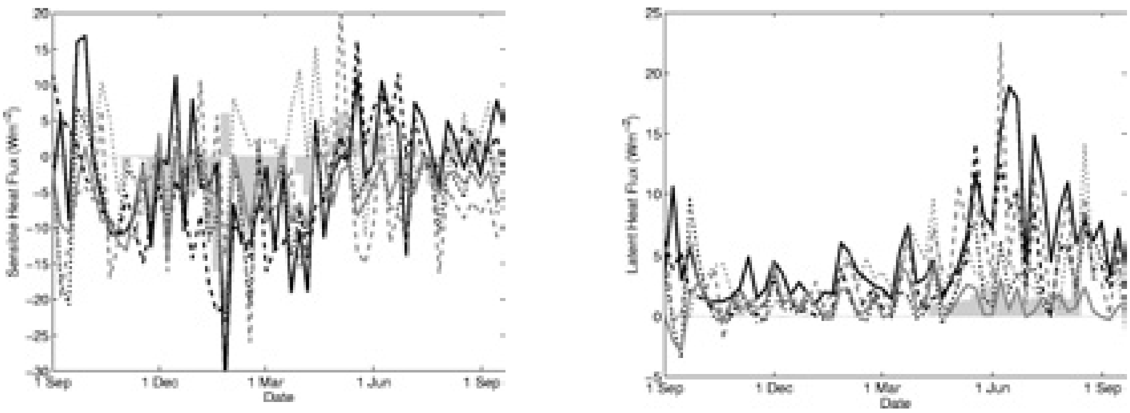

Figure 8.As Figure 2, but for weekly averaged turbulent (left) sensible and (right) latent heat flux..

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