

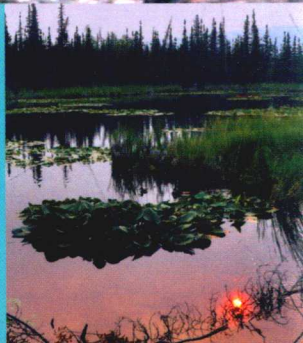
Editors HUGH FRENCH | OLAV SLAYMAKER

Changing Cold Environments

A Canadian Perspective



 WILEY-BLACKWELL



Changing Cold Environments

A Canadian Perspective

Editors

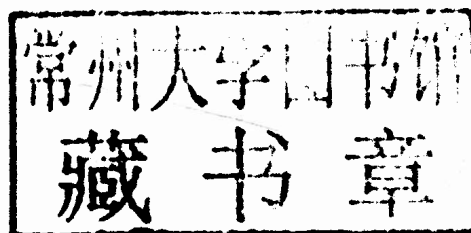
Hugh French

Professor Emeritus, University of Ottawa

and

Olav Slaymaker

Professor Emeritus, University of British Columbia



 **WILEY-BLACKWELL**

A John Wiley & Sons, Ltd., Publication

This edition first published 2012 © 2012 by John Wiley & Sons, Ltd

Wiley-Blackwell is an imprint of John Wiley & Sons, formed by the merger of Wiley's global Scientific, Technical and Medical business with Blackwell Publishing.

Registered office: John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial offices: 9600 Garsington Road, Oxford, OX4 2DQ, UK

The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

111 River Street, Hoboken, NJ 07030-5774, USA

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com/wiley-blackwell.

The right of the author to be identified as the author of this work has been asserted in accordance with the UK Copyright, Designs and Patents Act 1988.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by the UK Copyright, Designs and Patents Act 1988, without the prior permission of the publisher.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Library of Congress Cataloging-in-Publication Data

French, Hugh.

Changing Cold Environments: A Canadian Perspective / edited by Hugh French and Olav Slaymaker.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-470-69968-3 (cloth) – ISBN 978-0-470-69969-0 (pbk.)

1. Cold regions. 2. Natural history—Canada. 3. Natural history—Canada, Northern. 4. Physical geography—Canada. 5. Physical geography—Canada, Northern. I. Title.

GB648.15.F74 2012

551.310971—dc23

2011017016

A catalogue record for this book is available from the British Library.

This book is published in the following electronic formats: ePDF 9781119950165; Wiley Online Library 9781119950172; ePub 9781119951087; Mobi 9781119951094

Set in 10.5/12.5pt Minion by Thomson Digital, India

Printed and bound in Singapore by Markono Print Media Pte Ltd

First Impression 2012

Changing Cold Environments

List of Contributors

The Editors

HUGH FRENCH taught at the University of Ottawa in the Departments of Geography (1967–2003), Geology (1982–1992) and Earth Sciences (1998–2003). He has broad experience of the cold non-glacial regions of the world. He is now Emeritus Professor, University of Ottawa and Adjunct Professor, Department of Geography, University of Victoria.

OLAV SLAYMAKER taught at the University College of Wales, Aberystwyth (1964–1968) and at the University of British Columbia in the Department of Geography (1968–2004). He is a geomorphologist interested in global environmental change. He has extensive experience of mountainous terrain and geomorphic systems. He is now Emeritus Professor, University of British Columbia.

Contributing Authors

DAVID BARBER holds the Canada Research Chair of Arctic System Science and is Director, Centre for Earth Observation Science, University of Manitoba. His research focuses on the causes and consequences of climate forcing of sea ice in the Arctic.

ROGER BARRY is former Director of the National Snow and Ice Data Center (NSIDC), in the Cooperative Institute for Research in Environmental Sciences (CIRES) and Distinguished Professor Emeritus in Geography, University of Colorado, USA. He has published 20 books and over 250 papers on Arctic and mountain climates, climate change and cryospheric science. He currently holds a Humboldt Prize Fellowship, 2009–2012.

CHRIS BURN holds the NSERC Northern Research Chair for Permafrost in the Yukon and Northwest Territories. He is Professor in the Department of Geography and Environmental Studies, Carleton University, Ottawa. He conducts field research in the Yukon and western Arctic Canada.

DAVID EVANS is Reader in Geography, Durham University, UK. He is a glacial geomorphologist who works in a wide range of glaciated landscapes, including Iceland, Arctic and western Canada, New Zealand and Northern Scandinavia. He has published

widely on glacial landforms, glacial sedimentology and stratigraphy, and Quaternary palaeoglaciology.

KONRAD GAJEWSKI is Professor of Geography and Director of the Laboratory for Paleoclimatology and Climatology, University of Ottawa. He has published widely in the fields of arctic and subarctic paleoclimatology, paleoecology and paleolimnology.

JIM GARDNER is a physical geographer who has taught at the University of Waterloo and the University of Manitoba. He specializes in mountain geomorphology and hazards. He is now Adjunct Professor, Department of Geography, University of Victoria.

RICHARD KELLY is Professor, Department of Geography and Environmental Management, University of Waterloo and a group leader in the Interdisciplinary Centre on Climate change, University of Waterloo. His research interests are in snow and ice hydrology, especially the measurement of snow and ice from Earth-observing remote-sensing instruments

GITA LAIDLER is Assistant Professor, Department of Geography and Environmental Studies, Carleton University, Ottawa. Her research concerns the changes imposed on Inuit communities and their lifestyle by changing climate and associated environmental change. She works in Igloolik, Iqaluit and other northern settlements.

JENNIFER LUKOVICH is Research Associate at the Centre for Earth Observation Science (CEOS), University of Manitoba. Her research interests include the investigation of sea ice and atmospheric dynamics in the Arctic.

GLEN MACDONALD taught in the Department of Geography, McMaster University, 1984–1995, and is currently Director of the Institute of the Environment and Sustainability of the University of California Los Angeles, USA. He teaches in the UCLA departments of Geography and Ecology and Evolutionary Biology and conducts research on climate change, arctic and alpine tree lines, northern soil carbon and water resources.

JOHN POMEROY is Canada Research Chair in Water Resources and Climate Change and Director of the Centre for Hydrology, University of Saskatchewan. His research interests include snow hydrology, forest hydrology, frozen soils, and the hydrology of the mountains, prairies and northern Canada.

TERRY PROWSE is Professor of Geography, University of Victoria, and holds the Chair in Climate Impacts and Water Resources, University of Victoria. Current research interests include circumpolar cold regions hydrology and environmental effects of river ice.

MARK SERREZE is the Director of the National Snow and Ice Data Center (NSIDC) and Professor of Geography, University of Colorado, Boulder, USA. He has published extensively upon climate change and cryospheric issues.

MING-KO WOO is Emeritus Professor, School of Geography and Earth Science, McMaster University, and a professional hydrologist of the American Institute of Hydrology. He has conducted field studies in Canada and China, specializing in snow, permafrost, wetlands and water-related subjects.

Preface

Eighteen years ago we edited a volume called *Canada's Cold Environments*. It was a type of regional physical geography of northern Canada and its mountains. In its preface we set the tone by noting that 'coldness is a pervasive Canadian characteristic, part of the nation's culture and history'. In spite of many indications that Canada has become a warmer place since 1993, coldness remains a pervasive and distinct Canadian characteristic. There is, however, sufficient change in the hydroclimate, and indeed in the 'oekumene' of Canada as a whole (those parts of Canada that are inhabited by permanent residents), to warrant a fresh look at Canada's changing physical environment. Moreover, the Canadian experience is a useful barometer against which similar changes in the other regions of the northern Polar World can be compared.

Whether or not the globe as a whole is experiencing a long term warming trend fuelled by increasing greenhouse-gas concentrations in the atmosphere or a cyclic and short term warming trend caused by geophysical drivers such as solar emission or changing Sun-Earth relations is a mega-problem upon which we are not willing or competent to comment. What we do know is that Canada's cold regions, and especially its arctic regions, are experiencing rates of warming that are unprecedented in the past millennium. We also know that human demands on the natural resources of Canada's cold regions are growing apace.

The most obvious changes relate to shrinking glaciers, reductions in annual sea ice extent, and longer duration of ice-free periods on rivers and lakes. These are physical realities that can be readily observed and measured. Others are more subtle. But these changes coincide with a period of increasing global demographic pressure and intensifying resource demand at a time when it is becoming clear that globalization is upon us. In addition, the sovereignty of Canada's Arctic may soon be questioned as the possibility of an ice-free sea route between Europe and the emerging economies of Southeast Asia becomes increasingly a reality. The net effect of these accelerating processes is to focus new and urgent attention on Canada's cold environments.

We have assembled 14 experts, in contrast with just nine in our earlier book. All have extensive Canadian experience. The new topics which now require separate chapter treatment are sea ice, river and lake ice, remotely sensed imagery and the ways in which the northern indigenous peoples (in this case the Inuit) interact with this rapidly changing environment. We have also given more space to ecological changes and provide deeper understanding of the glacial and postglacial histories of our cold

environments. In this way we hope to counteract some of the more emotional responses to contemporary environmental change. It is our conviction that environments have always changed and continue to evolve. In fact, as a society, we can even be grateful for the rapid environmental changes of the last 2.5 million years (the Quaternary); many would argue that such changes have been partially responsible for stimulating the evolution of *Homo sapiens*. Thus, our emphasis upon current and future change indicates our own belief in our continued evolution.

In this volume we, and our contributors, have attempted to provide an authoritative, yet readable scientific statement about the nature of Canada's changing cold environments. We have not attempted a comprehensive geographic coverage. Instead, we have focused on the distinctive attributes of Canada's changing cold environments. Their temporal and spatial variability is central, as is the interaction of northern peoples with those environments. As in our earlier volume, the constraints and opportunities created by coldness for human activity are also considered.

We have both seen a progressive evolution of Canada as a pre-eminent cold-climate nation over the last 40 years. Thus, our objectives in undertaking an assessment of this change have been threefold. The first has been to provide insight into the ways in which biophysical processes are influenced by coldness at a range of scales. The second has been to provide a biophysical context for understanding the human geography of Canada. The third has been to examine current rates of environmental change and, if projected into the future, how those rates of change will affect Canada's cold environments.

We wish to thank the authors of the individual chapters for their willingness to join us in this venture and to share their experience and wisdom. Needless to say, not all of them provided material in a timely and efficient manner. But they have all achieved, in our opinion, the desired mix of authoritative information and accessible style. Our cartographers, Ole Heggen and Eric Leinberger, deserve special recognition for the quality of the figures and images.

Any lack of coherence and errors of fact or interpretation are our responsibility and we request your indulgence.

Hugh French
Olav Slaymaker
June 2011

Glossary

Active layer	The layer of ground above permafrost that freezes and thaws each year.
Albedo	The reflectivity of an entity. An albedo of 0 (1) indicates that all solar energy is absorbed (reflected).
Alp	A shoulder high on the side of a glacial trough.
Arctic	(1) Geographic definition: the area north of the Arctic Circle (latitude $66^{\circ} 33'N$); (2) Climatic definition: the region where the warmest monthly mean air temperature does not exceed $10^{\circ}C$ and the coldest is below $0^{\circ}C$.
AVHRR	(Airborne Very High Resolution Radiometer). A sensor system deployed on NOAA satellites that returns 1.1 km resolution images of the Earth.
Bubnov	A unit for quantifying rates of slope retreat or ground loss.
Co-management	A co-management agreement is a management plan that specifies the objectives, partners to the agreement, and rights and responsibilities of the partners.
Community-based research	A participatory approach to research in resource and environmental management.
Comprehensive land claims	Aboriginal title to land.
Cryosphere	Ice sheets, glaciers, sea ice, river and lake ice, snow, and both seasonally and perennially frozen ground.
Debris flow	A form of mass movement of a mixture of water, rocks, fine sediments and/or organic debris.
Degree days	(1) <i>Growing degree-days</i> (GDD) are usually measured from a threshold value of $5.5^{\circ}C$ and defined as $\Sigma(Ta - 5.5)^{\circ}C$ where Ta is mean air temperature for the day and Σ indicates that successive daily values are summed. (2) <i>Freezing degree-days</i> (FDD) are the summation of the daily temperatures that are below $0^{\circ}C$.

Disjunc	(as used in ecology) An organism that is found in two locations that is separated by more than the usual dispersal distance.
ELA	(Equilibrium Line Altitude) A notional altitudinal line on a glacier where ablation balances accumulation.
First year sea ice	Sea ice that has not yet survived a winter, with thicknesses ranging from 30 cm at the beginning of the season to 2 m near the end of the season.
Flaw lead	A linear crack in sea ice created by divergent winds and/or shear zones.
Frazil ice	Small spicules of ice that nucleate in river flow under a slight amount of supercooling.
Freshet	The rise in spring river flow, typically due to snowmelt.
Geopolitics	An area of geographical enquiry which considers space to be important in understanding the constitution of international relations.
Governance	(1) the nature of organizations and (2) the nature of the relations between organizations.
Ground ice	Ice formed in freezing and frozen ground. Ground ice may constitute between 40–60% by volume of the upper 10 m of permafrost.
Ground temperature envelope	The graphical representation of the annual range in ground temperature with depth.
Ice jam	An accumulation of fragmented ice floes that constricts the flow of water.
Jokulhlaup	Catastrophic drainage of a subglacial or ice-dammed lake.
Krummholz	The shrub form of trees, such as spruce, which are typically found in stressed environments.
Latent heat of fusion	The heat given off or taken in by a material during a change of phase between liquid and solid states.
Milankovitch effects	Periodicities in the Earth's orbit due to changes in eccentricity (~100 000 y), axial tilt (~41 000 y) and precession of the spring equinox (~23 000 y).
MYI	(Multi-year sea ice) Ice that has survived a summer melt season, with thicknesses ranging from 2–4 m as ice grows beneath the ice sheet.
Natural hazard	The coincidence in space or time of extreme geophysical events and human use systems.
Neoglaciation	A local scale glacial advance that occurred during the Holocene Epoch.
Nival regime streamflow	The discharge pattern of a stream that results from the melt of seasonal snow and ice.
Nordicité	A concept coined by the Québec geographer Louis-Edmond Hamelin to quantify what is understood by the term 'northern'.

NDVI	(Normalized Difference Vegetation Index) A numerical indicator applied to remote sensing data that compares visible light and near infrared reflectance from the Earth's surface to determine vegetation density and health.
Pancake ice	Circular disks resulting from the accumulation of frazil ice crystals with a range in size from a few centimeters to 3–5 metres in diameter.
Paraglacial	Non-glacial processes conditioned by glaciation.
Passive microwave radiation	Naturally emitted radiation that can be observed by a radiometer.
Periglacial	An environment with permafrost and intense frost activity.
Permafrost	Ground (soil or rock) that remains at or below 0 °C for at least two years.
Phylogeography	The distribution of organisms using molecular data.
Phytogeography	The distribution and abundance of plants.
Polar amplification	Amplified temperature trends over the Arctic Ocean compared with the rest of the hemisphere.
Polynya	A region of open water, where sea ice would normally be expected to occur, established by persistent divergent winds or upwelling of warm water.
Proxy records	Sources such as tree rings, pollen, ice and sediment cores that allow past climatic conditions to be inferred.
Quaternary Period	The last 2.6 million years (approximately) during which time many major glaciations occurred.
Relict	(as used in ecology). A taxon surviving in a region after being eliminated from most of its original distribution.
Sea ice	An entity of frozen water that floats on the surface of the ocean.
Sea ice concentration anomaly	Departures in sea ice concentration from a climatological mean.
Sea ice dynamics	Sea ice motion and circulation that is driven by atmospheric circulation and winds and/or ocean currents.
Sea ice extent	A measurement defined as the area with at least 15% ice concentration that is used to monitor the edge of sea ice.
Seasonally frozen ground	Ground that remains frozen for part of the year.
Sediment cascade	The sequence of sediment production, transport and deposition.
Snow albedo feedback	The effect of changing the land surface from a snow-covered surface (high albedo) to a snow free surface (low albedo).
SCA	(Snowcover area) The extent of snow cover within a given area.
Snow stratigraphy	The configuration of layering in the snow pack and variations in snow properties through the vertical profile.
Snow sublimation	The process by which snow evaporates.

SWE	(Snow-water equivalent). The amount of melted water from a column of snow.
Socioecological system	A system viewed with the understanding that what matters to humans is the environment as filtered through culture-specific perception and behaviour.
Spectral reflectance	A critical property for differentiating surfaces in remote sensing.
Subarctic	A climatic and/or ecological term that refers to those areas where the mean monthly air temperatures do not exceed +10 °C for more than four months and where the coldest is below 0 °C.
Thermal offset	The difference in mean annual temperature between the ground surface and the top of permafrost.
Thermal conductivity	The ability of a material to conduct heat.
Thermal diffusivity	The ability of a medium to propagate a temperature disturbance.
Thermokarst	The process by which terrain is modified when ice-rich permafrost thaws.
Timberline	The upper, altitudinal, limit of continuous closed forest stand. (1) In mountains, the forest may reach its upper limit as a closed stand and cease abruptly as a sharp line against a treeless alpine zone. (2) Alternatively, the forest gradually dissolves from a dense closed stand (timberline) to isolated trees and finally to stunted individuals.
Transient layer	The layer at the top of permafrost that thaws from time to time due to climatic variation. The timescale for development of the transient layer is unfortunately undefined precisely, but it may be considered to be on the order of tens to hundreds of years.
Treeline	The northern, latitudinal, limit of trees. The northern boundary of the subarctic approximates the treeline.
Vulnerability	The ability of an individual or group of people to anticipate, avoid, cope with and resist the impacts of a natural hazard.
Wind chill	An index of the degree of atmospheric cooling experienced by a person. It is usually expressed as the temperature in still air that would correspond to the cooling generated by a particular combination of temperature and wind speed.

Contents

List of Contributors	xi
Preface	xiii
Glossary	xv
 PART ONE SPATIAL AND TEMPORAL VARIABILITY OF CANADA'S COLD ENVIRONMENTS	 1
 1 Cold Canada and the Changing Cryosphere	 3
<i>Hugh French and Olav Slaymaker</i>	
1.1 Introduction	3
1.2 The Cryosphere	4
1.3 Cold Canada	10
1.4 Cold Climates	15
1.5 Arctic and Alpine Considerations	19
1.6 Canada's Physical Geography	21
References	24
Discussion Questions	25
Some Useful Internet Sources	25
 2 The Late Quaternary Glaciation of Northern Canada	 26
<i>David Evans</i>	
2.1 Introduction	26
2.2 Landforms and the Late Quaternary Glaciations	26
2.3 Late Quaternary Sea level Change and its Relationship to Glaciation History	39
2.4 Late Quaternary Glaciation and Deglacial History	39
2.5 Wider Implications of Canadian Arctic Ice Sheet Dynamics	42
2.6 Holocene Glacial Events	44
References	44
Discussion Questions	47
Some Useful Internet Sources	47

3	The Evolution of Polar Desert and Tundra Ecosystems	48
	<i>Konrad Gajewski</i>	
3.1	Introduction	48
3.2	The Nature of the Environment	49
3.3	Ecology of Arctic Plants	51
3.4	Vegetation Zonation	53
3.5	Arctic Oases	55
3.6	Long term Evolution of Canadian Arctic Ecosystems	56
3.7	The Quaternary	58
3.8	Postglacial Climate and Vegetation Change in Arctic Canada	59
	References	61
	Discussion Questions	64
	Some Useful Internet Sources	65
4	Remote Sensing and Canadian Snow Climatology	66
	<i>Richard Kelly</i>	
4.1	Introduction	66
4.2	The Importance of Snow in the Earth System	66
4.3	Snow Measurements in Canada	67
4.4	Remote Sensing of Snow	70
4.5	Snow Variations Inferred from Remote Sensing Observations	77
4.6	Discussion	82
4.7	Conclusion	82
	References	83
	Discussion Questions	86
	Some Useful Internet Sources	86
	PART TWO THE CHANGING CRYOSPHERE	87
5	The Changing Climates	89
	<i>Roger Barry and Mark Serreze</i>	
5.1	Introduction	89
5.2	Late Pliocene	89
5.3	Quaternary History	90
5.4	Postglacial Conditions	91
5.5	The Last Two Millennia	92
5.6	Recent Changes	94
5.7	The Future	96
	References	101
	Discussion Questions	103
	Some Useful Internet Sources	104
6	Snow and Runoff: Processes, Sensitivity and Vulnerability	105
	<i>Ming-Ko Woo and John Pomeroy</i>	
6.1	Introduction	105
6.2	Snow Accumulation	107

6.3 Land Cover	109
6.4 Snow Ablation	111
6.5 Snowmelt Runoff Processes	113
6.6 Streamflow	117
6.7 Snowmelt Floods in Large Basins	118
6.8 Snow Vulnerability	122
References	123
Discussion Questions	125
Some Useful Internet Sources	125
7 Permafrost Distribution and Stability	126
<i>Chris Burn</i>	
7.1 Introduction	126
7.2 Distribution of Permafrost	130
7.3 Thermal Regime of Permafrost	134
7.4 Permafrost and Climate Change	136
7.5 Conclusions	143
References	143
Discussion Questions	146
Some Useful Internet Sources	146
8 Sea Ice in Canada	147
<i>David Barber and Jennifer Lukovich</i>	
8.1 Introduction	147
8.2 What is Sea Ice?	147
8.3 The Physical Nature of Sea Ice	148
8.4 Spatial and Temporal Distribution of Sea Ice	150
8.5 Sea Ice and Climate Change	158
8.6 Implications for Northern Communities, Economic Development and the Environment	160
References	160
Discussion Questions	162
Some Useful Internet Sources	162
9 Lake and River Ice in Canada	163
<i>Terry Prowse</i>	
9.1 Introduction	163
9.2 Role in the Climate System	168
9.3 Climatic Controls	168
9.4 Historical Trends and Linkages to Climate	169
9.5 Future Ice Regime Projections	172
9.6 Implications of Ice Regime Changes	173
References	179
Discussion Questions	181
Some Useful Internet Sources	181

PART THREE THE EVER-CHANGING SCENERY	183
10 Climate Change and the Central Canadian Treeline	185
<i>Glen MacDonald</i>	
10.1 Introduction	185
10.2 The Central Canadian Treeline Zone Today	186
10.3 Current Warming at the Central Canadian Treeline	188
10.4 Response of the Central Canadian Treeline to Warming Temperatures	191
References	195
Discussion Questions	198
Some Useful Internet Sources	199
11 Geomorphic Change in Northern Canada	200
<i>Hugh French</i>	
11.1 Introduction	200
11.2 Lessons from the Past	202
11.3 Freezing, Thawing and Bedrock Instability	205
11.4 Warming Permafrost	205
11.5 Changes in Azonal Processes	213
11.6 Geotechnical Implications of Warming Permafrost	216
11.7 Conclusions	217
References	218
Discussion Questions	221
Some Useful Internet Sources	221
12 Geomorphic Change in Canada's Temperate Mountains	222
<i>Olav Slaymaker</i>	
12.1 Introduction	222
12.2 Present Morphology	223
12.3 Spatial Variability of Ecology and Morphology	224
12.4 Hydroclimate and Cryospheric Phenomena	228
12.5 Rates and Kinds of Geomorphic Processes	234
12.6 Disturbances Regimes and Landscape Transitions	240
12.7 Conclusions	242
References	243
Discussion Questions	246
Some Useful Internet Sources	246
13 Risk from Cold-climate Hazards in the Canadian Cordillera	247
<i>Jim Gardner</i>	
13.1 Introduction	247
13.2 Cold-climate Hazards	247
13.3 Risk and Climate Variability	249
13.4 Conclusions	264

References	264
Discussion Questions	266
Some Useful Internet Sources	266
14 Societal Aspects of Changing Cold Environments	267
<i>Gita Laidler</i>	
14.1 Introduction	267
14.2 Cultural Pursuits and Indigenous Rights	268
14.3 Local and Broader Implications of Changing Sea Ice	281
14.4 Northern Governance	292
14.5 Conclusions	294
References	295
Discussion Questions	300
Some Useful Internet Sources	300
15 The Changing Canadian Cryosphere, Globalization and Global Environmental Change	301
<i>Olav Slaymaker and Hugh French</i>	
15.1 Introduction	301
15.2 The Question of Scale	302
15.3 Adaptive Management	308
15.4 Globalization	310
15.5 Conclusion	310
References	311
Discussion Questions	312
Some Useful Internet Sources	312
Index	313