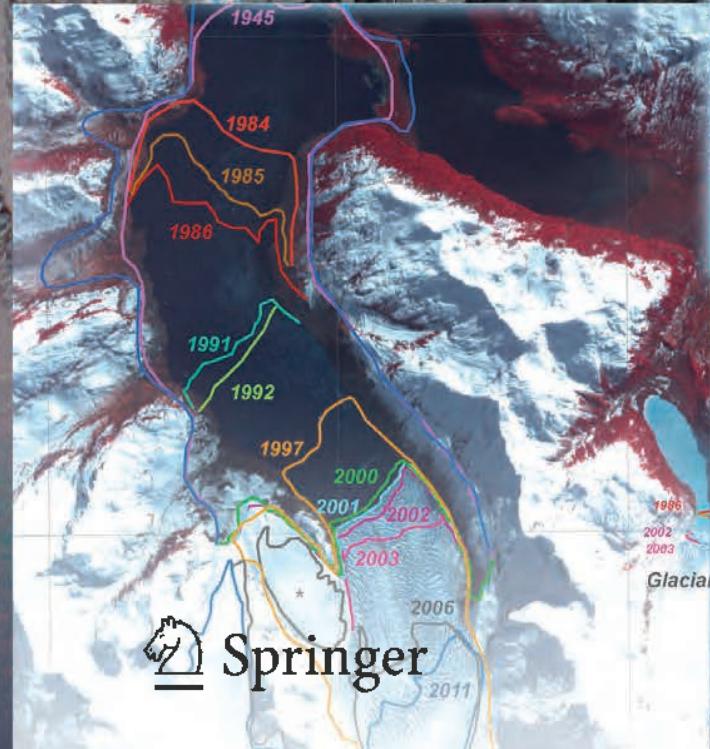
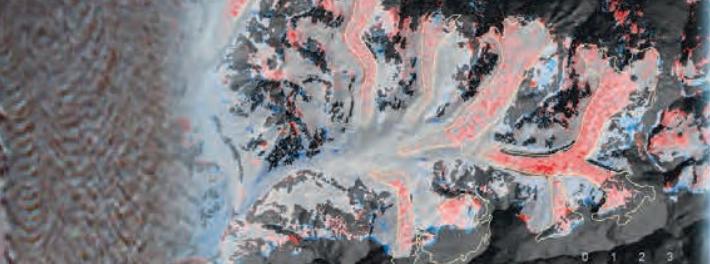
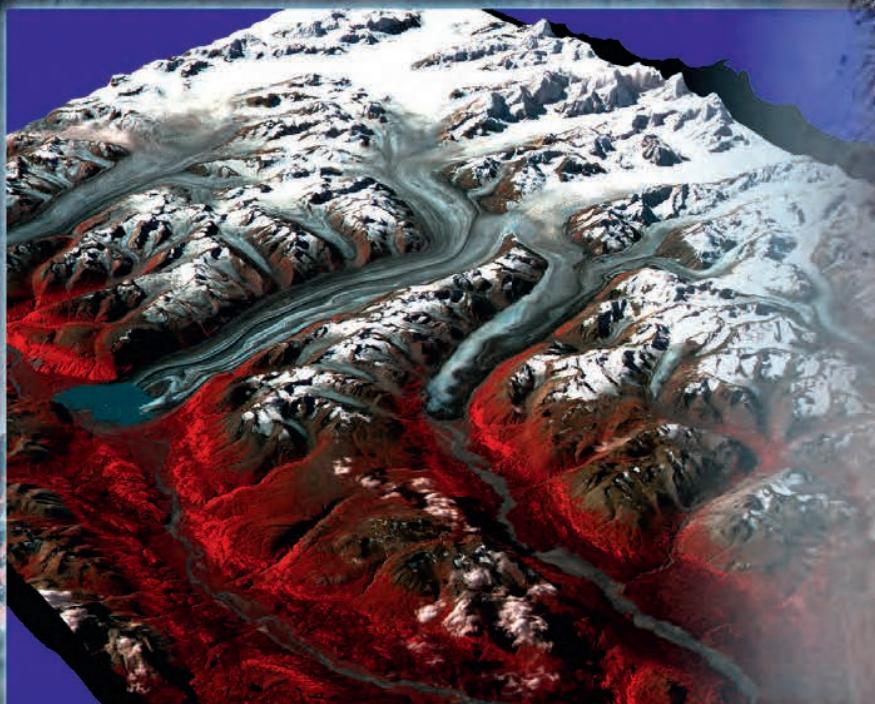


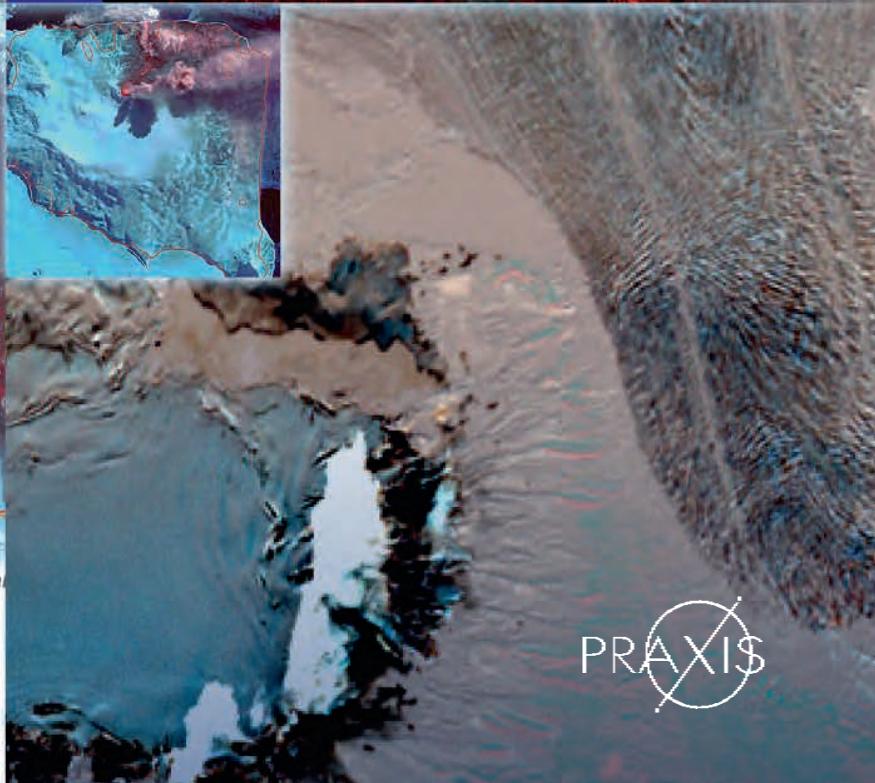
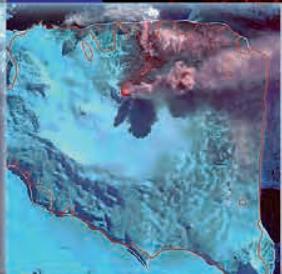


Global Land Ice Measurements from Space

Jeffrey S. Kargel
Gregory J. Leonard
Michael P. Bishop
Andreas Kääb
and Bruce H. Raup *Editors*



Springer



PRAXIS

Springer Praxis Books

Geophysical Sciences

For further volumes:
<http://www.springer.com/series/4110>

Jeffrey S. Kargel • Gregory J. Leonard
Michael P. Bishop • Andreas Kääb
Bruce H. Raup
Editors

Global Land Ice Measurements from Space



Editors

Jeffrey S. Kargel
Department of Hydrology and Water Resources
University of Arizona
Tucson, AZ
USA

Gregory J. Leonard
Department of Hydrology and Water Resources
Global Land Ice Measurements from Space
University of Arizona
Tucson, AZ
USA

Michael P. Bishop
Department of Geography
Texas A&M University
College Station, TX
USA

Andreas Kääb
Department of Geosciences
University of Oslo
Oslo
Norway

Bruce H. Raup
University of Colorado Boulder
Boulder, CO
USA

Published in association with Praxis Publishing Chichester, UK

Additional material to this book can be downloaded from <http://extras.springer.com/>

ISSN 1615-9748
ISBN 978-3-540-79817-0 ISBN 978-3-540-79818-7 (eBook)
DOI 10.1007/978-3-540-79818-7
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014943116

© Springer-Verlag Berlin Heidelberg 2014

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Contents

Click on any "sticky note" to contact authors and request a free PDF copy

Dedication

List of contributors

Foreword by Hugh H. Kieffer

Acknowledgments

Online supplemental material

Chapter receipt information

List of figures

Disclaimer: GLIMS is not a border authority

List of tables

List of abbreviations and acronyms

About the editors

 **Prologue**

 **1 Introduction: Global glacier monitoring—a long-term task integrating *in situ* observations and remote sensing**

Michael Zemp, Richard Armstrong, Isabelle Gärtner-Roer, Wilfried Haeberli, Martin Hoelzle, Andreas Kääb, Jeffrey S. Kargel, Siri Jodha S. Khalsa, Gregory J. Leonard, Frank Paul, and Bruce H. Raup

- 1.1 Why this book? 1
- 1.2 Perennial surface ice on land 2
- 1.2.1 Definitions 2
- 1.2.2 Global coverage 3
- 1.3 Glaciers and climate 4

xv	1.3.1 <i>Formation of glaciers and their dynamical controls</i>	4
xvii	1.3.2 <i>Glacier reactions to climate change, and response times</i>	5
xxv	1.3.3 <i>Reporting glacier change rates</i>	5
xxix	1.4 International glacier monitoring	6
xxxi	1.4.1 <i>History of international glacier monitoring in the 19th and 20th centuries</i>	6
xxxiii	1.4.2 <i>The Global Terrestrial Network for Glaciers (GTN-G)</i>	8
xxxv	1.4.3 <i>Available datasets</i>	9
xlvi	1.4.4 <i>Challenges of the 21st century</i>	9
xlii	1.5 Glacier observations from space	12
lxxi	1.5.1 <i>Satellite observations in GTN-G</i>	12
lxxii	1.5.2 <i>Possible applications</i>	13
lxxiii	1.5.3 <i>Challenges</i>	14
lxxiv	1.6 Integrative glacier change assessments	15
lxxv	1.7 Synopsis and organization of the book	15
lxxvi	1.8 Conclusions	16
lxxvii	1.9 Acknowledgments	17
lxxviii	1.10 References	17

 **2 Theoretical foundations of remote sensing for glacier assessment and mapping**

Michael P. Bishop, Andrew B.G. Bush, Roberto Furfarò, Alan R. Gillespie, Dorothy K. Hall, Umesh K. Haritashya, and John F. Shroder Jr.

- 2.1 Introduction 23
- 2.2 Radiation transfer cascade 24
- 2.2.1 *Solar irradiance* 24
- 2.2.2 *Surface irradiance* 25
- 2.2.3 *Surface reflectance* 30

Click on any "sticky note" to contact authors and request a free PDF copy

vi Contents

2.2.4 <i>Surface emission</i>	31	4.2.1 <i>Radiometric calibration</i>	76
2.3 Surface–energy interactions	32	4.2.2 <i>Geometric preprocessing</i>	76
2.3.1 <i>Snow</i>	32	4.3 Multispectral methods	78
2.3.2 <i>Glaciers</i>	34	4.3.1 <i>Spectral reflectance of glacier surfaces</i>	78
2.3.3 <i>Water</i>	35	4.3.2 <i>Image classification approaches</i>	79
2.4 Complications	37	4.3.3 <i>Image-processing techniques</i>	81
2.5 Space-based information extraction	37	4.3.4 <i>Postprocessing and GIS work flow</i>	86
2.5.1 <i>Snow cover</i>	37	4.4 Mapping debris-covered ice	86
2.5.2 <i>Ice sheets</i>	38	4.5 Thermal imaging	89
2.5.3 <i>Alpine glacier mapping</i>	38	4.6 Microwave/SAR methods	89
2.5.4 <i>Debris-covered glaciers</i>	39	4.7 Spectral change detection and temporal data merging	91
2.5.5 <i>Snow line and ELA</i>	40	4.7.1 <i>Overview</i>	91
2.5.6 <i>Ice flow velocities</i>	41	4.7.2 <i>Image change evaluation by subtraction of multispectral anniversary pairs (ICESMAP)</i>	95
2.6 Numerical modeling	42	4.8 Ice flow	98
2.6.1 <i>Climate modeling</i>	42	4.8.1 <i>Image choice and preprocessing for image matching</i>	100
2.6.2 <i>Energy balance modeling</i>	43	4.8.2 <i>Image-matching techniques</i>	100
2.6.3 <i>Glacier mass balance modeling</i>	45	4.8.3 <i>Postprocessing and analysis</i>	102
2.7 Conclusions	46	4.8.4 Accuracy	102
2.8 Acknowledgments	46	4.8.5 <i>SAR offset tracking and interferometry</i>	103
2.9 Notation	47	4.9 Challenges, conclusions, and perspectives	105
2.10 References	48	4.10 Acknowledgments	106
4.11 References		4.11 References	106
3 Radiative transfer modeling in the cryosphere		5 Digital terrain modeling and glacier topographic characterization	
 <i>Roberto Furfaro, Alberto Previti, Paolo Picca, Jeffrey S. Kargel, and Michael P. Bishop</i>		 <i>Duncan J. Quincey, Michael P. Bishop, Andreas Kääb, Etienne Berthier, Boris Flach, Tobias Bolch, Manfred Buchroithner, Ulrich Kamp, Siri Jodha S. Khalsa, Thierry Toutin, Umesh K. Haritashya, Adina E. Racoviteanu, John F. Shroder, and Bruce H. Raup</i>	
3.1 Introduction	53	5.1 Introduction	113
3.2 Radiative transfer modeling of glacier surfaces	55	5.2 Background	114
3.2.1 <i>RT modeling approach for glacier surfaces</i>	56	5.3 Digital elevation model generation	116
3.2.2 Radiative transfer equation in layered mixtures of snow, ice, and debris	58	5.3.1 Source data	116
3.2.3 <i>Radiative transfer equation in glacier lake waters</i>	59	5.3.2 <i>Aerial and satellite image stereoscopy</i>	117
3.3 Optical properties of snow, ice, debris, mixtures, and glacier lake water	60	5.3.3 <i>Ground control points</i>	118
3.3.1 <i>Snow</i>	61	5.3.4 Software packages	120
3.3.2 <i>Glacier ice</i>	61	5.3.5 <i>Postprocessing (interpolation and smoothing)</i>	121
3.3.3 <i>Rock debris</i>	62	5.3.6 Data fusion	122
3.3.4 <i>Mixtures</i>	63	5.4 DEM error and uncertainty	123
3.3.5 <i>Glacier lake water</i>	63	5.4.1 <i>Representation of DEM error and uncertainty</i>	123
3.4 Numerical solution of the RTE	64	5.4.2 Type and origin of errors	123
3.5 Glacier radiative transfer simulation examples	66	5.5 Geomorphometry	124
3.6 Conclusions	70	5.5.1 <i>Geomorphometric land surface parameters</i>	125
3.7 References	71	5.5.2 Scale-dependent analysis	125
4 Glacier mapping and monitoring using multispectral data		5.5.3 Topographic radiation modeling	127
 <i>Andreas Kääb, Tobias Bolch, Kimberly Casey, Torborg Heid, Jeffrey S. Kargel, Gregory J. Leonard, Frank Paul, and Bruce H. Raup</i>		5.5.4 Altitude functions	127
4.1 Introduction	75		
4.2 Image preprocessing	76		

Click on any "sticky note" to contact authors and request a free PDF copy

Contents vii

5.5.5 <i>Glacier elevation changes and mass balance calculations</i>	128	7.6.1 <i>Ingest quality control steps</i>	176
5.6 <i>Glacier mapping</i>	131	7.6.2 <i>Representation of measurement error</i>	179
5.6.1 <i>Pattern recognition</i>	133	7.6.3 <i>Derived parameters in the database</i>	180
5.6.2 <i>Artificial intelligence techniques</i>	134	7.7 <i>Conclusion</i>	180
5.6.3 <i>Object-oriented mapping</i>	135	7.8 <i>Acknowledgments</i>	181
5.7 <i>Discussion</i>	135	7.9 <i>References</i>	181
5.8 <i>Conclusions</i>	138		
5.9 <i>Acknowledgments</i>	138		
5.10 <i>References</i>	138		
6 ASTER datasets and derived products for global glacier monitoring		8 Glacier fluctuations and dynamics around the margin of the Greenland Ice Sheet	
 <i>Bhaskar Ramachandran, John Dwyer, Bruce H. Raup, and Jeffrey S. Kargel</i>	145	 <i>Leigh A. Stearns and Hester Jiskoot</i>	183
6.1 <i>Introduction</i>	145	8.1 <i>Greenland glaciology</i>	183
6.2 <i>ASTER Data Access and Use Policy</i>	146	8.1.1 <i>Ice sheet mass changes</i>	184
6.3 <i>ASTER data</i>	147	8.2 <i>Case Study 1: Central East Greenland margin fluctuations and climate sensitivity from a GLIMS Glacier Inventory and ASTER GDEM</i>	186
6.3.1 <i>Performance of ASTER VNIR, SWIR, and TIR</i>	147	8.2.1 <i>Introduction</i>	186
6.4 <i>ASTER data-processing stream</i>	152	8.2.2 <i>Methods</i>	188
6.4.1 <i>Standard Level 1A and Level 1B</i>	152	8.2.3 <i>Results</i>	189
6.4.2 <i>ASTER standard higher level products</i>	153	8.3 <i>Case Study 2: A comparison of high-rate GPS and ASTER-derived measurements on Helheim Glacier</i>	193
6.5 <i>ASTER data for GLIMS: STARS, DARs, gain settings, and image seasons</i>	159	8.3.1 <i>Introduction</i>	193
6.6 <i>Acknowledgments</i>	160	8.3.2 <i>Data</i>	193
6.7 <i>References</i>	161	8.3.3 <i>Results</i>	196
7 Quality in the GLIMS Glacier Database		8.4 <i>Discussion and conclusion</i>	199
 <i>Bruce H. Raup, Siri Jodha S. Khalsa, Richard L. Armstrong, William A. Sneed, Gordon S. Hamilton, Frank Paul, Fiona Cawkwell, Matthew J. Beedle, Brian P. Menounos, Roger D. Wheate, Helmut Rott, Liu Shiyin, Li Xin, Shangguan Donghui, Cheng Guodong, Jeffrey S. Kargel, Chris F. Larsen, Bruce F. Molnia, Joni L. Kincaid, Andrew Klein, and Vladimir Konovalov</i>	163	8.5 <i>Acknowledgments</i>	200
7.1 <i>Introduction</i>	163	8.6 <i>References</i>	200
7.2 <i>Standard methods and tools</i>	164		
7.3 <i>Accuracy and precision in glacier mapping</i>	164		
7.4 <i>Glacier analysis comparison experiments (GLACE)</i>	166	9 Remote sensing of recent glacier changes in the Canadian Arctic	
7.4.1 <i>GLACE 1 and GLACE 2</i>	166	 <i>Martin Sharp, David O. Burgess, Fiona Cawkwell, Luke Copland, James A. Davis, Evelyn K. Dowdeswell, Julian A. Dowdeswell, Alex S. Gardner, Douglas Mair, Libo Wang, Scott N. Williamson, Gabriel J. Wolken, and Faye Wyatt</i>	205
7.4.2 <i>GLACE 2A and GLACE 3A (manual digitization)</i>	167	9.1 <i>Introduction</i>	205
7.5 <i>GLACE results</i>	168	9.2 <i>Regional context</i>	206
7.5.1 <i>GLACE 1 and GLACE 2</i>	168	9.2.1 <i>Geology and physiography</i>	206
7.5.2 <i>GLACE 2A and GLACE 3A</i>	171	9.2.2 <i>Climate and recent climate trends in the Canadian Arctic</i>	206
7.5.3 <i>Discussion</i>	173	9.2.3 <i>Glacier characteristics</i>	209
7.6 <i>GLIMS Glacier Database and the data ingest process</i>	176	9.3 <i>Special topics: regional glacier mass balance and proxy indicators</i>	210
		9.3.1 <i>Surface mass balance and mass balance changes</i>	210
		9.3.2 <i>Summer melt</i>	211
		9.3.3 <i>Ice flow and iceberg-calving fluxes</i>	213
		9.4 <i>Case studies</i>	214
		9.4.1 <i>Surge-type glaciers</i>	214
		9.4.2 <i>Northern Ellesmere Island ice shelves</i>	216
		9.5 <i>Regional synthesis: Recent changes in</i>	

Click on any "sticky note" to contact authors and request a free PDF copy

equilibrium line altitude and glacier extent	217	11.2.3 <i>Glacier characteristics—Kenai Fjords National Park</i>	243
9.5.1 <i>Methodology</i>	217	11.2.4 <i>Glacier characteristics—Katmai National Park and Preserve</i>	244
9.5.2 <i>Results</i>	219	11.3 Procedures for analysis of glacier changes	245
9.6 Key issue	220	11.3.1 <i>Imagery classification</i>	245
9.6.1 <i>Changes in glacier surface elevation, volume, and mass; sea level contributions</i>	220	11.3.2 <i>Complicating issues</i>	247
9.7 Summary and conclusions	224	11.3.3 <i>Manual editing</i>	247
9.8 Acknowledgments	225	11.4 Satellite imagery interpretation accuracy	247
9.9 References	225	11.5 Areal extent—glacier ice	248
10 A digital glacier database for Svalbard		11.5.1 <i>Kenai Fjords National Park</i>	248
 Max König, Christopher Nuth, Jack Kohler, Geir Moholdt, and Rickard Pettersen	229	11.5.2 <i>Katmai National Park and Preserve</i>	248
10.1 Introduction	229	11.6 Terminus position measurements	250
10.2 Regional context	230	11.6.1 <i>Methodology</i>	250
10.3 Database structure	230	11.6.2 <i>Kenai Fjords National Park</i>	251
10.4 Data	231	11.6.3 <i>Katmai National Park and Preserve</i>	256
10.4.1 <i>The original Topographic Map Series of Svalbard (S100)—1936/ 1966/1971</i>	231	11.7 Discussion and conclusions	259
10.4.2 <i>The 1990 photogrammetric survey</i>	232	11.8 References	260
10.4.3 <i>The satellite dataset</i>	232		
10.5 Methodology	233		
10.5.1 <i>Creation of glacier outlines from cartographic data for the 1936/1966/1971 dataset</i>	233	12 Glacier-dammed ice-marginal lakes of Alaska	
10.5.2 <i>Creation of outlines from cartographic data for the 1990 dataset</i>	233	 David F.G. Wolfe, Jeffrey S. Kargel, and Gregory J. Leonard	263
10.5.3 <i>Creation of outlines from satellite data for the 2001–2010 dataset</i>	233	12.1 Introduction	264
10.5.4 <i>Glacier and snow patches smaller than 1 km²</i>	234	12.2 Regional context	265
10.6 Results	234	12.2.1 <i>Geographic setting</i>	265
10.7 Conclusions and future perspectives	238	12.2.2 <i>Climate</i>	267
10.8 Acknowledgments	238	12.2.3 <i>Previous research</i>	267
10.9 References	238	12.3 Methods	268
11 Alaska: Glaciers of Kenai Fjords National Park and Katmai National Parks and Preserve		12.3.1 <i>Horizontal attributes</i>	271
 Bruce A. Giffen, Dorothy K. Hall, and Janet Y.L. Chien	241	12.3.2 <i>Mean glacier altitude (MGA)</i>	271
11.1 Introduction	241	12.3.3 <i>Glacier stream order (complexity)</i>	271
11.2 Regional context	242	12.3.4 <i>Glacier surface gradient</i>	271
11.2.1 <i>Geographic/topographic/environmental setting</i>	242	12.3.5 <i>Damming glacier origin and terminus types, and minimum–maximum altitudes</i>	271
11.2.2 <i>Climate</i>	243	12.3.6 <i>Aspects of ice dams and damming glaciers</i>	272
		12.4 Results	272
		12.4.1 <i>Changes over time: Lake-damming glaciers</i>	273
		12.4.2 <i>Changes over time: Glacier-dammed lake population</i>	276
		12.5 Case study: Iceberg Lake	280
		12.5.1 Overview	280
		12.5.2 Satellite observations	283
		12.5.3 Field observations	284
		12.5.4 Satellite era hydrology	286
		12.5.5 Possible causes of Iceberg Lake's dynamical evolution	289
		12.6 Discussion and conclusions	291
		12.7 Acknowledgments	292
		12.8 References	293

Click on any "sticky note" to contact authors and request a free PDF copy

Contents ix

13 Multispectral image analysis of glaciers and glacier lakes in the Chugach Mountains, Alaska	
	
<i>Jeffrey S. Kargel, Matthew J. Beedle, Andrew B.G. Bush, Francisco Carreño, Elena Castellanos, Umesh K. Haritashya, Gregory J. Leonard, Javier Lillo, Ivan Lopez, Mark Pleasants, Edward Pollock, and David F.G. Wolfe</i>	
297	
13.1 Introduction	297
13.2 Regional context	299
13.2.1 <i>Geological context</i>	299
13.2.2 <i>Climatic context: Descriptive overview and downscaled model</i>	301
13.2.3 <i>Regional significance of glaciers in the Chugach/St. Elias Mountains</i>	304
13.3 Case studies: Glacier inventorying and assessment of glacier dynamics	306
13.3.1 <i>A preliminary inventory of the Bering–Malaspina glacier complex</i>	306
13.3.2 <i>Glaciers of College Fiord: Harvard Glacier and Yale Glacier</i>	312
13.3.3 <i>Scott Glacier</i>	319
13.3.4 <i>Glaciers of the Copper River corridor: Childs, Miles, and Allen Glaciers</i>	319
13.4 Conclusions	328
13.5 Acknowledgments	329
13.6 References	329

14 Remote sensing of glaciers in the Canadian Cordillera, western Canada	
	
<i>Roger D. Wheate, Etienne Berthier, Tobias Bolch, Brian P. Menounos, Joseph M. Shea, John J. Clague, and Erik Schiefer</i>	
333	
14.1 Introduction	333
14.2 Regional context	334
14.2.1 <i>Topographic setting</i>	334
14.2.2 <i>Climate</i>	334
14.2.3 <i>Glacier distribution and characteristics</i>	334
14.3 Special topics and case studies	336
14.3.1 <i>Glacier hazards</i>	336
14.3.2 <i>Glacier changes</i>	339
14.4 Regional glacier inventories and synthesis	344
14.4.1 <i>British Columbia and Alberta</i>	344
14.4.2 <i>Yukon</i>	346
14.5 Concluding remarks	351
14.6 Acknowledgments	351
14.7 References	351

15 ASTER and DEM change assessment of glaciers near Hoodoo Mountain, British Columbia, Canada	
	
<i>Jeffrey S. Kargel, Gregory J. Leonard, Roger D. Wheate, and Benjamin Edwards</i>	
353	
15.1 Introduction	353
15.2 Geologic and climatic context	354
15.3 Special topics	355
15.3.1 <i>ASTER image differencing</i>	355
15.3.2 <i>Topographic differencing of Hoodoo Mountain and vicinity: Analysis of four time series of DEMs</i>	360
15.3.3 <i>Mass balance of glaciers in the Hoodoo Mountain study region</i>	363
15.3.4 <i>Ground and air photo assessment of glacier changes on Hoodoo Mountain and vicinity</i>	364
15.3.5 <i>Glacier and climate changes in the vicinity of Hoodoo Mountain</i>	369
15.4 Synthesis and conclusions	372
15.5 Acknowledgments	372
15.6 References	372
16 Glaciers of the Ragged Range, Nahanni National Park Reserve, Northwest Territories, Canada	
	
<i>Michael N. Demuth, Philip Wilson, and Dana Haggarty</i>	
375	
16.1 Introduction	375
16.2 Geographic, social, and climatic context	376
16.3 Glacier inventory and morphometry	377
16.4 Regional synthesis	377
16.5 Recommendations for further work	381
16.6 Acknowledgments	382
16.7 References	382
17 Glaciers and perennial snowfields of the U.S. Cordillera	
	
<i>Andrew G. Fountain, Hassan J. Basagic IV, Charles Cannon, Mark Devisser, Matthew J. Hoffman, Jeffrey S. Kargel, Gregory J. Leonard, Kristina Thorneycroft, and Steve Wilson</i>	
385	
17.1 Introduction	385
17.2 Regional context	386
17.2.1 <i>Geologic context</i>	386
17.2.2 <i>Climatic context</i>	387
17.3 Methods	388
17.4 Results	388
17.4.1 <i>California</i>	389
17.4.2 <i>Colorado</i>	389
17.4.3 <i>Idaho</i>	390
17.4.4 <i>Montana</i>	390
17.4.5 <i>Nevada</i>	391

Click on any "sticky note" to contact authors and request a free PDF copy

x Contents

17.4.6 <i>Oregon</i>	391	19.2.2 <i>Glacier changes</i>	429
17.4.7 <i>Washington</i>	392	19.2.3 <i>Previous glacier inventories</i>	430
17.4.8 <i>Wyoming</i>	393	19.2.4 <i>Digital glacier outlines from topographical maps (N50)</i>	430
17.4.9 <i>Advancing glaciers</i>	393	19.3 Methodology (derivation of glacier outlines from Landsat)	431
17.5 Case studies using ASTER	394	19.3.1 <i>Selection of Landsat scenes</i>	431
17.5.1 <i>Grinnell Glacier, Glacier National Park, Montana</i>	394	19.3.2 <i>Glacier-mapping methods</i>	432
17.5.2 <i>Glacier changes on Mt. Rainier, Washington, assessed using ASTER and MASTER multispectral and thermal imagery</i>	395	19.4 Case studies and special topics	433
17.5.3 <i>ASTER and field studies of Blue Glacier, Olympic Mountains, Washington</i>	403	19.4.1 <i>Glacier size distribution</i>	433
17.6 Summary and conclusions	403	19.4.2 <i>Assessing area changes in Jotunheimen and Svartisen</i>	433
17.7 Acknowledgments	405	19.4.3 <i>Uncertainties</i>	434
17.8 References	405	19.5 Conclusions	435
		19.6 Acknowledgments	435
		19.7 References	436

18 Remote sensing of mountain glaciers and ice caps in Iceland



*Oddur Sigurðsson,
Richard S. Williams, Jr.,
Sandro Martinis, and Ulrich Münzer*

18.1 Introduction	409
18.1.1 <i>History of mapping Iceland's glaciers</i>	409
18.1.2 <i>Scientific analysis of Iceland's glaciers</i>	410
18.1.3 <i>Air and spaceborne imaging and remote-sensing analysis of Iceland's glaciers</i>	411
18.2 Regional context	412
18.2.1 <i>Geography and geology</i>	412
18.2.2 <i>Climate and climate variability</i>	414
18.3 Special topics and methodology	415
18.3.1 <i>Types of glaciers</i>	415
18.3.2 <i>History of Iceland's glacier variations</i>	416
18.3.3 <i>Identifying the outline, transient snow line, and firn line of glaciers</i>	417
18.3.4 <i>Jökulhlaups</i>	417
18.4 Three case studies	418
18.4.1 <i>Transient tephra lines</i>	418
18.4.2 <i>Classification of the Vatnajökull ice cap according to three different outlines</i>	418
18.4.3 <i>The impact of the 2004 jökulhlaup on glacier dynamics of Skeiðarárjökull</i>	419
18.5 Regional summary	421
18.6 Acknowledgments	422
18.7 References	422

19 Norway



Liss M. Andreassen, Frank Paul, and Jon Endre Hausberg

19.1 Introduction	427
19.2 Regional context	427
19.2.1 <i>Glacier observations</i>	428

20 European Alps



*Frank Paul, Yves Arnaud,
Roberto Ranzi, and Helmut Rott*

20.1 Regional context	439
20.1.1 <i>Geographic and topographic characteristics</i>	439
20.1.2 <i>Climatic conditions</i>	440
20.1.3 <i>Glacier characteristics</i>	441
20.1.4 <i>Glacier observations</i>	443
20.1.5 <i>Satellite data</i>	443
20.2 Austria	444
20.2.1 <i>Regional context</i>	444
20.2.2 <i>Austrian glacier inventories</i>	445
20.2.3 <i>Satellite-based study of glaciers in the Stubai Alpen</i>	445
20.2.4 <i>Conclusion</i>	447
20.3 France	447
20.3.1 <i>Introduction</i>	447
20.3.2 <i>Examples of remote sensing-based studies in the French Alps</i>	448
20.4 Italy	451
20.4.1 <i>Introduction</i>	451
20.4.2 <i>Glacier retreat: glaciers in the Sabbione, Pustertal, and Dolomites regions</i>	452
20.4.3 <i>The Belvedere and Miage debris-covered glaciers</i>	452
20.4.4 <i>Albedo and energy balance of Mandrone Glacier</i>	455
20.5 Switzerland	456
20.5.1 <i>Methods for glacier inventory creation</i>	456
20.5.2 <i>Results</i>	457
20.5.3 <i>Conclusions</i>	458
20.6 Synthesis and outlook	459
20.7 Acknowledgments	460
20.8 References	460

Click on any "sticky note" to contact authors and request a free PDF copy

Contents xi

21 Satellite inventory of glaciers in Turkey		22.5 Results	498
 <i>Mehmet Akif Sarıkaya and Ahmet Emre Tekeli</i>	465	22.5.1 <i>Glacial change in the Munkh Khairkhan range</i>	498
21.1 Introduction	465	22.5.2 <i>Glacial change in the Tavan Bogd range</i>	499
21.2 Regional context	466	22.6 Discussion	502
21.2.1 <i>Topography</i>	466	22.6.1 <i>Munkh Khairkhan range</i>	502
21.2.2 <i>Climate</i>	467	22.6.2 <i>Tavan Bogd range</i>	505
21.3 Methods	467	22.7 Conclusions	506
21.4 Occurrences of glaciers	468	22.8 Acknowledgments	506
21.4.1 <i>Glaciers in the Southeastern Taurus Mountains</i>	468	22.9 References	507
21.4.2 <i>Glaciers in the coastal ranges of the eastern Black Sea</i>	471		
21.4.3 <i>Glaciers on individual mountains</i>	472		
21.5 Rock glaciers	476		
21.5.1 <i>Kavuşşahap Mountains</i>	476		
21.5.2 <i>Soğanlı Mountains</i>	476		
21.5.3 <i>Rize Mountains</i>	476		
21.5.4 <i>Karaçal Mountains</i>	477		
21.5.5 <i>Mt. Erciyes</i>	477		
21.5.6 <i>Mercan Mountains</i>	477		
21.5.7 <i>Esence Mountains</i>	477		
21.6 Summary and conclusion	477		
21.7 Acknowledgment	478		
21.8 References	478		
22 Recent glacier changes in the Mongolian Altai Mountains: Case studies from Munkh Khairkhan and Tavan Bogd			
 <i>Brandon S. Krumwiede, Ulrich Kamp, Gregory J. Leonard, Jeffrey S. Kargel, Avirmed Dashtseren, and Michael Walther</i>	481		
22.1 Introduction	481		
22.2 Regional background	482		
22.2.1 <i>Quaternary history of glaciers in the Mongolian Altai</i>	482		
22.2.2 <i>Recent history of glaciers in the Mongolian Altai</i>	483		
22.3 Regional context and study areas	484		
22.3.1 <i>Geography and climate</i>	484		
22.3.2 <i>Munkh Khairkhan range</i>	485		
22.3.3 <i>Tavan Bogd range</i>	486		
22.4 Data and methods	487		
22.4.1 <i>Topographic maps</i>	487		
22.4.2 <i>Satellite imagery</i>	487		
22.4.3 <i>GPS data</i>	489		
22.4.4 <i>Pan-sharpening</i>	489		
22.4.5 <i>Glacier mapping</i>	490		
22.4.6 <i>Error analysis (area accuracy and change precision)</i>	492		
22.4.7 <i>Digital elevation models</i>	493		
22.4.8 <i>DEM-derived datasets</i>	496		
22.4.9 <i>Geomorphometric analysis</i>	497		
23 Remote sensing of glaciers in Afghanistan and Pakistan			
 <i>Michael P. Bishop, John F. Shroder Jr., Ghazanfar Ali, Andrew B.G. Bush, Umesh K. Haritashya, Rakhshan Roohi, Mehmet Akif Sarıkaya, and Brandon J. Weihns</i>	509		
23.1 Introduction	509		
23.2 Regional context	510		
23.2.1 <i>Geology</i>	510		
23.2.2 <i>Topography</i>	513		
23.2.3 <i>Climate</i>	513		
23.2.4 <i>Glaciers</i>	514		
23.3 Methodology	518		
23.4 Case studies	520		
23.4.1 <i>Afghanistan</i>	520		
23.4.2 <i>Pakistan</i>	529		
23.5 Regional synthesis	543		
23.5.1 <i>Afghanistan</i>	543		
23.5.2 <i>Pakistan</i>	543		
23.6 Acknowledgments	544		
23.7 References	544		
24 Himalayan glaciers (India, Bhutan, Nepal): Satellite observations of thinning and retreat			
 <i>Adina E. Racoviteanu, Yves Arnaud, I.M. Baghuna, Samjwal R. Bajracharya, Etienne Berthier, Rakesh Bhambri, Tobias Bolch, Martin Byrne, Ravinder K. Chaujar, Regula Frauenfelder, Andreas Kääb, Ulrich Kamp, Jeffrey S. Kargel, Anil V. Kulkarni, Gregory J. Leonard, Pradeep K. Mool, and I. Sosná</i>	549		
24.1 Overview	549		
24.2 Regional context	550		
24.2.1 <i>Geographic, geologic, and topographic setting</i>	550		
24.2.2 <i>Climate dynamics and glacier regimes</i>	552		
24.2.3 <i>Previous glacier mapping and observations</i>	553		
24.3 Case studies and specific topics	553		
24.3.1 <i>Sikkim Himalaya: glacier area change, 1960–2000</i>	553		

Click on any "sticky note" to contact authors and request a free PDF copy

24.3.2	<i>Khumbu and Garhwal Himalaya: glacier area and thickness changes, 1960s–2000s</i>	555
24.3.3	<i>Everest region, Nepal: geomorphologic and surface reflectance changes, 2001–2005</i>	560
24.3.4	<i>Brahmaputra River basin: glacier area, volume, and velocity changes, 1970s through to about 2000</i>	564
24.3.5	<i>Ladakh, northwestern Indian Himalaya: glacier length/area change, 1975–2008</i>	569
24.3.6	<i>Himachal Pradesh and Uttarakhand, western Indian Himalaya: glacier area change, 1962–2004</i>	571
24.3.7	<i>Himachal Pradesh, western Himalaya: geodetic mass balance estimates, 1999–2004</i>	573
24.4	Summary and outlook	575
24.5	Appendix—image differencing: methodology, limitations, and errors	575
24.6	Acknowledgments	577
24.7	References	577
25	Glaciers in China and their variations	
	 <i>Liu Shiyin, Shangguan Donghui, Xu Junli, Wang Xin, Yao Xiaojun, Jiang Zongli, Guo Wanqin, Lu Anxin, Zhang Shiqiang, Ye Baisheng, Li Zhen, Wei Junfeng, and Wu Lizong</i>	
25.1	Introduction to glaciers in China	583
25.2	Regional context	584
25.3	Methods for glacier change monitoring by remote sensing	585
25.4	Glacier area extent change	586
25.4.1	<i>Glacier change since the Little Ice Age maximum</i>	586
25.4.2	<i>Glacier change during recent decades</i>	588
25.5	Change in surface elevations	591
25.5.1	<i>Koxkar Glacier</i>	591
25.5.2	<i>Yanglong River</i>	593
25.6	Surface movement derived by satellite remote sensing	595
25.6.1	<i>Justification</i>	595
25.6.2	<i>Glacier velocity derived using D-InSAR and SAR feature-tracking methods</i>	597
25.6.3	<i>Glacier velocity derived by optical images</i>	598
25.7	Special topics: hydrological aspects of Chinese glacier dynamics	599
25.7.1	<i>Special Topic 1: glacier hazards in the Upper Yarlung Zangbo River basin, China</i>	599
25.7.2	<i>Special Topic 2: glacier water resources in western China provinces</i>	601
25.8	Summary and future prospects	605
25.9	Acknowledgments	605
25.10	References	605
26	Remote sensing of rapidly diminishing tropical glaciers in the northern Andes	
	 <i>Todd Albert, Andrew Klein, Joni L. Kincaid, Christian Huggel, Adina E. Racoviteanu, Yves Arnaud, Walter Silverio, and Jorge Luis Ceballos</i>	
26.1	Introduction	609
26.2	Regional context	610
26.3	Special topics and case studies	610
26.3.1	<i>Quelccaya, Peru</i>	610
26.3.2	<i>Cordillera Vilcanota, Peru</i>	614
26.3.3	<i>Nevado Coropuna, Peru</i>	616
26.3.4	<i>Cordillera Blanca, Peru</i>	616
26.3.5	<i>Colombia</i>	622
26.3.6	<i>Tres Cruces, Bolivia</i>	625
26.3.7	<i>Venezuela</i>	630
26.4	Regional synthesis	632
26.5	Discussion	633
26.6	Acknowledgments	635
26.7	References	635
27	A new glacier inventory for the Southern Patagonia Icefield and areal changes 1986–2000	
	 <i>Gino Casassa, José Luis Rodríguez, and Thomas Loriaux</i>	
27.1	Introduction	639
27.2	Regional context	641
27.2.1	<i>Geographic setting</i>	641
27.2.2	<i>Climate</i>	641
27.2.3	<i>Glacier characteristics and changes</i>	641
27.3	Data and methods	643
27.3.1	<i>Satellite imagery</i>	643
27.3.2	<i>Glacier delineation</i>	643
27.3.3	<i>Ice divides</i>	643
27.3.4	<i>Equilibrium line altitudes (ELAs)</i>	644
27.3.5	<i>Glacier area errors</i>	644
27.4	Results	645
27.4.1	<i>Glacier inventory</i>	645
27.4.2	<i>Glacier variations 1986–2000</i>	648
27.5	Discussion	649
27.6	Conclusions	657
27.7	Acknowledgments	658
27.8	References	658
28	First glacier inventory and recent glacier variations on Isla Grande de Tierra del Fuego and adjacent islands in Southern Chile	
	 <i>Francisca Bown, Andrés Rivera, Pablo Zenteno, Claudio Bravo, and Fiona Cawkwell</i>	
28.1	Introduction	661
28.2	Regional context	662
28.3	Methods	664

Click on any "sticky note" to contact authors and request a free PDF copy

Contents **xiii**

28.3.1	<i>Satellite data acquisition and preprocessing</i>	664	30.2.1	<i>Geologic context</i>	719
28.3.2	<i>Glacier extent classification and ice divide digitization</i>	664	30.2.2	<i>Climatic context</i>	719
28.3.3	<i>Frontal variations</i>	666	30.2.3	<i>Summary of known glacier dynamics</i>	720
28.3.4	<i>Errors</i>	666	30.3	<i>Methodology</i>	721
28.4	<i>Results</i>	666	30.3.1	<i>Evaluation of ASTER-derived DEMs for the Antarctic Peninsula</i>	721
28.4.1	<i>Glacier inventory</i>	666	30.4	<i>Case studies and special topics</i>	725
28.4.2	<i>Frontal variations</i>	667	30.4.1	<i>Monitoring glacier change in the northeastern Antarctic Peninsula</i>	725
28.5	<i>Discussion</i>	669	30.4.2	<i>Glaciers of Vega Island and James Ross Island</i>	725
28.5.1	<i>Some possible explanations</i>	671	30.4.3	<i>Former tributaries of Prince Gustav Channel (PGC) Ice Shelf</i>	727
28.6	<i>Conclusions</i>	671	30.4.4	<i>Former tributaries of Larsen A Ice Shelf</i>	727
28.7	<i>Acknowledgments</i>	673	30.4.5	<i>Former tributaries of Larsen B Ice Shelf</i>	727
28.8	<i>References</i>	673	30.4.6	<i>Monitoring changes and breakup events on the Wilkins Ice Shelf</i>	728
29	New Zealand's glaciers		30.4.7	<i>Variation of radar glacier zone boundaries in the northeastern Antarctic Peninsula</i>	731
	Trevor J. Chinn, Jeffrey S. Kargel, Gregory J. Leonard, Umesh K. Haritashya, and Mark Pleasants	675	30.5	<i>Regional synthesis</i>	736
29.1	<i>Introduction</i>	676	30.6	<i>Summary and conclusions</i>	736
29.2	<i>Regional context</i>	678	30.7	<i>Acknowledgments</i>	737
29.2.1	<i>Geologic setting</i>	678	30.8	<i>References</i>	737
29.2.2	<i>Climatic context and glacier overview</i>	679	31	Mapping blue-ice areas and crevasses in West Antarctica using ASTER images, GPS, and radar measurements	
29.3	<i>New Zealand's historical glacier dynamics</i>	681		Andrés Rivera, Fiona Cawkwell, Anja Wendt, and Rodrigo Zamora	743
29.3.1	<i>Early historical observations</i>	681	31.1	<i>Introduction</i>	743
29.3.2	<i>Franz Josef Glacier's long historical record</i>	682	31.2	<i>Blue-ice areas</i>	744
29.3.3	<i>Proxy mass balance from the Snowlines Program and aerial photography</i>	683	31.2.1	<i>Mapping BIA extent in the field and on imagery</i>	744
29.3.4	<i>Glacier responses since the end of the LIA</i>	683	31.2.2	<i>Interannual fluctuations in the extent of Patriot Hills' BIA</i>	746
29.4	<i>Remote-sensing case studies</i>	687	31.2.3	<i>Interannual fluctuation in the extent of other BIAs</i>	749
29.4.1	<i>ASTER observations of Mt. Ruapehu, North Island</i>	687	31.3	<i>Crevasse detection on satellite imagery</i>	750
29.4.2	<i>ASTER observations of small glaciers in the Southern Alps</i>	691	31.4	<i>Radio-echo sounding and ground-penetrating radar measurements</i>	752
29.4.3	<i>ASTER observations of Mt. Cook glaciers</i>	693	31.5	<i>Discussion</i>	753
29.5	<i>Special topics</i>	704	31.6	<i>Conclusions</i>	755
29.5.1	<i>Debris production and debris cover of New Zealand glaciers</i>	704	31.7	<i>Acknowledgments</i>	756
29.5.2	<i>New Zealand glacier and climate coupling</i>	706	31.8	<i>References</i>	756
29.6	<i>Conclusions</i>	710	32	Remote sensing of glaciers of the subantarctic islands	
29.7	<i>Acknowledgments</i>	711		J. Graham Cogley, Etienne Berthier, and Shawawn Donoghue	759
29.8	<i>References</i>	711	32.1	<i>Introduction</i>	759
30	Monitoring glacier changes on the Antarctic Peninsula		32.2	<i>The regional context</i>	759
	Jorge Arigony-Neto, Pedro Skvarca, Sebastián Marinsek, Matthias Braun, Angelika Humbert, Cláudio Wilson Mendes Júnior, and Ricardo Jaña	717	32.3	<i>Case studies</i>	762
30.1	<i>Introduction</i>	717	32.3.1	<i>Heard Island</i>	762
30.2	<i>Regional context</i>	719	32.3.2	<i>Kerguelen</i>	765
			32.3.3	<i>Montagu Island</i>	768

Click on any "sticky note" to contact authors and request a free PDF copy

32.4 Cartographic Inventory of the Subantarctic	771	33.3.7 <i>Glacier change in the Southern Ocean Super-Region</i>	804
32.5 Summary and conclusion	774	33.3.8 <i>Seasonal thaw in a blue-ice area of the Antarctic interior</i>	809
32.6 Acknowledgments	777	33.4 Summary discussion: What lies behind glacier fluctuations and general retreat?	810
32.7 References	777	33.4.1 <i>Global trends in glacier and ice sheet mass balance and sea level trends</i>	810
33 A world of changing glaciers:		33.4.2 <i>Global warming: first-order cause of modern-day retreat and thinning of glaciers</i>	810
 Summary and climatic context		33.4.3 <i>What drives variability in glacier responses to a changing global environment?</i>	813
<i>Jeffrey S. Kargel, Andrew B.G. Bush, J. Graham Cogley, Gregory J. Leonard, Bruce H. Raup, Claudio Smiraglia, Massimo Pecci, and Roberto Ranzi</i>	781	33.4.4 <i>Climate change is heterogeneous and multivariate</i>	813
33.1 Overview	781	33.4.5 <i>Variable response times as a further cause of heterogeneous glacier responses</i>	816
33.2 Summary: the foundations of glacier remote-sensing science (Chapters 2–7)	782	33.4.6 <i>Other causes of variability in the response dynamics of glaciers</i>	820
33.3 Super-regional narratives of glacier dynamics	784	33.4.7 <i>Little known or unknown causes with the potential to affect glaciers and us</i>	821
33.3.1 <i>Glacier changes in the Arctic Super-Region (Greenland and the Canadian High Arctic)</i>	785	33.5 Joe Public's two big questions	825
33.3.2 <i>Glacier changes in the North Atlantic Super-Region (Iceland–Norway–Sweden–Svalbard)</i>	790	33.6 Conclusions	828
33.3.3 <i>Glacier changes in the North American Cordilleran Super-Region (U.S. and western Canada)</i>	793	33.7 Acknowledgments	830
33.3.4 <i>Glacier changes in the Mediterranean Super-Region</i>	796	33.8 References	830
33.3.5 <i>Glacier changes in the South and Central Asia Super-Region</i>	799		
33.3.6 <i>Changes in glaciers of the Northern Andes</i>	803	Index	847