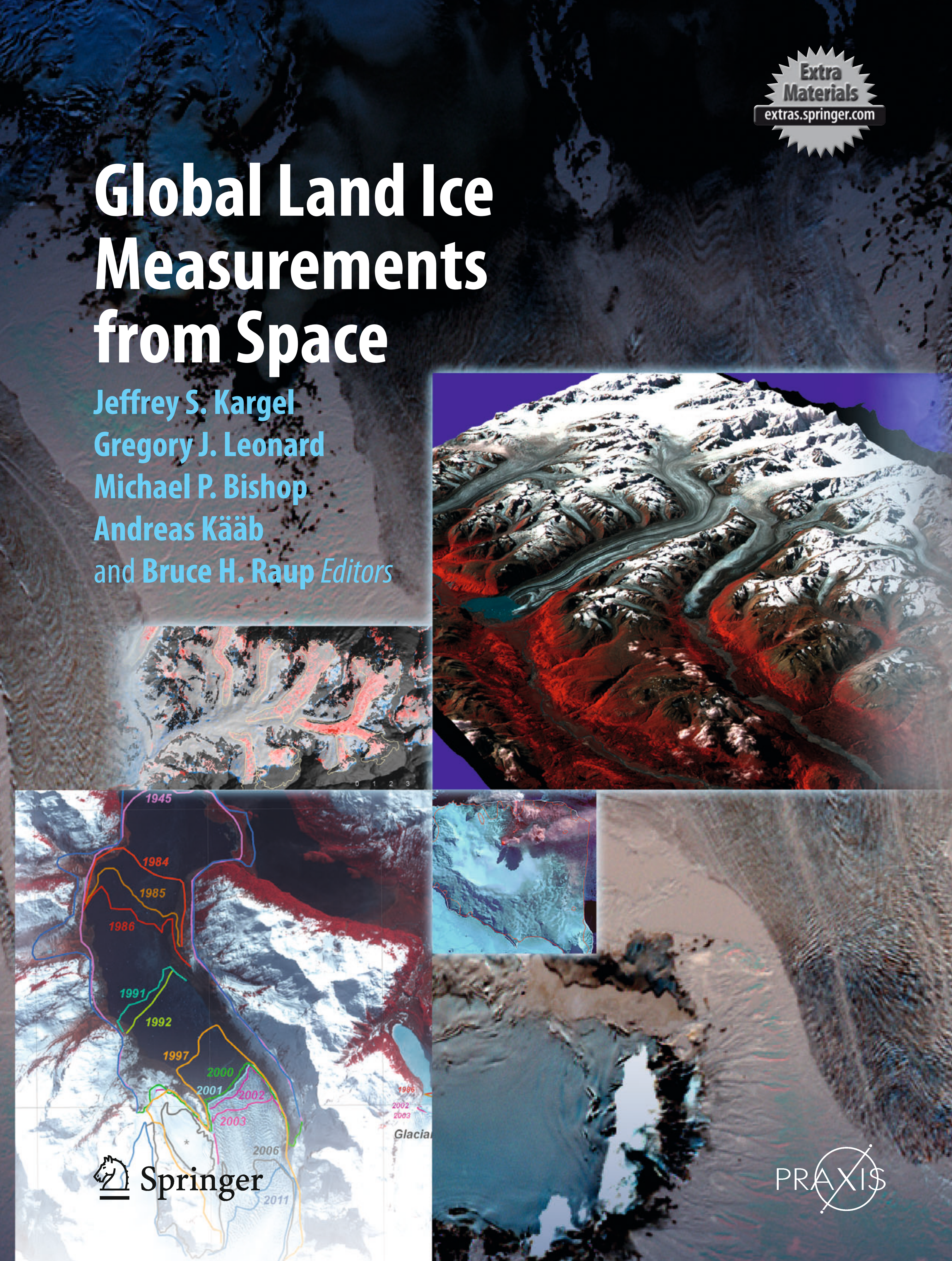
Global Land Ice Measurements from Space

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

Springer

PRAXIS

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
Tuscon, 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

10 A digital glacier database for Svalbard

11 Alaska: Glaciers of Kenai Fjords National Park and Katmai National Parks and Preserve

12 Glacier-dammed ice-marginal lakes of Alaska

Dedication

We dedicate this book to our families, who endured our absences from them and endured as well our dispositions, whether joyous or vexed, during our time on the book. In dedication we also recognize the world's land ice, those frozen lands from the majestic ice sheets of the white circumpolar realms, to the graceful valley glaciers and fast-disappearing glacier bits; and to those glaciers no longer here.

Contributors

The names of Chinese authors in this list are treated traditionally, with the family name appearing before the given name. Names are alphabetized by family name, which here appear in capitals.

Todd Albert
Department of Agriculture, Geosciences, &
Natural Resources, The University of Tennessee at
Martin, Martin, Tennessee, U.S.A.

Ghazanfar Ali
Water Resources & Glaciology Section, Global
Change Impact Studies Center (GCISC), National
Center for Physics Complex, Quaid-i-Azam
University, Islamabad, Pakistan

Liss M. Andreassen
Norwegian Water Resources & Energy
Directorate, Oslo, Norway; Department of
Geosciences, University of Oslo, Oslo, Norway

Jorge Arigony-Neto
Instituto Nacional de Ciência e Tecnologia da
Criosfera, Laboratório de Monitoramento da
Criosfera, Instituto de Ciências Humanas e da
Informação, Universidade Federal do Rio Grande,
Rio Grande, Brazil

Richard Armstrong
National Snow and Ice Data Center, University of
Colorado, Boulder, U.S.A.

Yves Arnaud
Laboratoire de Glaciologie et Géophysique de
l'Environnement, St Martin d'Hères, France;
Institut de Recherche pour le Développement,
France

I.M. Baghuna
Marine & Earth Sciences Group, Space
Applications Centre (ISRO), Ahmedabad, India

Samjwal R. Bajracharya
International Center for Integrated Mountain
Development, Kathmandu, Nepal

Victor R. Baker
Department of Hydrology & Water Resources,
University of Arizona, Tucson, Arizona, U.S.A.

Hassan J. Basagic IV
Department of Geology, Portland State University,
Portland, Oregon, U.S.A.

Matthew J. Beedle
Natural Resources & Environmental Studies
Institute & Geography Program, University of
Northern British Columbia—Northwest Campus,
Terrace, British Columbia, Canada

Etienne Berthier
Centre national de la recherche scientifique,
Laboratoire d'Etude en Géophysique et
Océanographie Spatiales, OMP-LEGOS,
Toulouse, France

Rakesh Bhambri
Guru Nanak Khalsa College, Haryana, India

Michael P. Bishop
Department of Geography, Texas A&M
University, College Station, Texas, U.S.A.
(*michael.bishop@tamu.edu*)

Tobias Bolch
Department of Geography, University of Zurich
Irchel, Zurich, Switzerland;
Institut für Kartographie, Technische Universität
Dresden, Germany

Francisca Bown
Centro de Estudios Científicos (CECs), Valdivia,
Chile

Matthias Braun
Institute of Geography, University of
Erlangen-Nuremberg, Erlangen, Germany

Claudio Bravo
Departamento de Geofísica, Universidad de Chile,
Santiago, Chile

Manfred Buchroithner
Fakultät Forst-, Geo- und Hydrowissenschaften
Fachrichtung, Geowissenschaften, Dresden,
Germany

David O. Burgess
Natural Resources Canada, National Glaciology
Program

Andrew B.G. Bush
Department of Earth & Atmospheric Sciences,
University of Alberta, Edmonton, Alberta, Canada

Martin Byrne
Department of Geography, University of
Montana, Missoula, MT 59812, U.S.A.

Charles Cannon
Department of Geology, Portland State University,
Portland, Oregon, U.S.A.

Francisco Carreño
Natural Área de Geología—ESCET, Universidad
Rey Juan Carlos, Móstoles, Madrid, Spain

Gino Casassa
Centro de Estudios Científicos, Valdivia, Chile;
Fundación Huilo Huilo, Las Condes,
Santiago, Chile

Kimberly Casey
CMNS-Earth System Science Interdisciplinary
Center, University of Maryland, College Park,
Maryland, U.S.A.

Elena Castellanos
Natural Área de Geología—ESCET, Universidad
Rey Juan Carlos, Tulipán 28933, Móstoles,
Madrid, Spain

Fiona Cawkwell
Department of Geography, University College
Cork, Cork, Ireland

Jorge Luis Ceballos
Institute of Meteorology, Hydrology &
Environmental Studies (IDEAM), Bogotá,
Colombia

Ravinder K. Chaujar
Wadia Institute of Himalayan Geology,
Dehradun, India

CHENG Guodong
Cold and Arid Regions Environmental and
Engineering Research Institute, Chinese Academy
of Sciences, Lanzhou, China

Janet Y.L. Chien
SAIC and Cryospheric Sciences Branch, NASA/
Goddard Space Flight Center, Greenbelt,
Maryland, U.S.A.

Trevor J. Chinn
Alpine & Polar Consultancy, Lake Hawea LGM,
Wanaka, New Zealand

John J. Clague
Earth Sciences, Simon Fraser University, Burnaby,
British Columbia, Canada

J. Graham Cogley
Department of Geography, Trent University,
Peterborough, Ontario, Canada

Luke Copland
Department of Geography, University of Ottawa,
Ottawa, Ontario, Canada

Avirmed Dashtseren
Geographical Institute, Mongolian Academy of
Sciences, Ulaanbaatar, Mongolia

James A. Davis
Department of Earth & Atmospheric Sciences,
University of Alberta

Michael N. Demuth
Natural Resources Canada—Geological Survey of
Canada—Cryosphere Geoscience Section,
Ottawa, Ontario, Canada

Mark Devisser
Department of Geography, Michigan State
University, East Lansing, Michigan, U.S.A.

Shavawn Donoghue
Antarctic Climate & Ecosystem Cooperative
Research Centre, Hobart, Australia;
Institute for Marine & Antarctic Studies,
University of Tasmania, Hobart, Australia

Evelyn K. Dowdeswell
Department of Geographical Sciences, University
of Bristol, Bristol, U.K.;
Scott Polar Research Institute, University of
Cambridge, Cambridge, U.K.

Julian A. Dowdeswell
Scott Polar Research Institute, University of
Cambridge, Cambridge, U.K.

John Dwyer
Landsat Data Continuity Mission Ground System,
U.S. Geological Survey, Earth Resources
Observation & Science Center, Sioux Falls,
South Dakota, U.S.A.

Benjamin Edwards
Department of Earth Sciences, Dickinson College,
Carlisle, Pennsylvania, U.S.A.

Boris Flach
Department of Geography, University of Zurich
Irchel, Zurich, Switzerland

Andrew G. Fountain
Department of Geology, Portland State University,
Portland, Oregon, U.S.A.

Regula Frauenfelder
Norwegian Geotechnical Institute, Oslo, Norway

Roberto Furfaro
Department of Systems & Industrial Engineering
and Department of Aerospace & Mechanical
Engineering, University of Arizona,
Tucson, Arizona, U.S.A.

Alex S. Gardner
Graduate School of Geography, Clark University,
Worcester, Massachusetts, U.S.A.

Isabelle Gärtner-Roer
World Glacier Monitoring Service, Department of
Geography, University of Zurich, Zurich,
Switzerland

Bruce A. Giffen
Alaska Regional Office, National Park Service,
Anchorage, Alaska, U.S.A.

Alan R. Gillespie
Department of Earth & Space Sciences, University
of Washington, Seattle, Washington, U.S.A.

GUO Wanqin
State Key Laboratory of Cryosphere Sciences,
Cold & Arid Regions of Environmental &
Engineering Research Institute, Chinese Academy
of Sciences, Lanzhou, China

Wilfried Haeberli
World Glacier Monitoring Service, Department of
Geography, University of Zurich, Zurich,
Switzerland

Dana Haggarty
Parks Canada—Nahanni National Park and
Reserve, Fort Simpson, Northwest Territories,
Canada

Dorothy K. Hall
Cryospheric Sciences Branch, NASA/Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

Gordon S. Hamilton
Climate Change Institute, University of Maine, Orono, Maine, U.S.A.

Umesh K. Haritashya
Department of Geology, University of Dayton, Dayton, Ohio, U.S.A.

Jon Endre Hausberg
Norwegian Water Resources and Energy Directorate, Oslo, Norway

Torborg Heid
Department of Geosciences, University of Oslo, Blindern, Oslo, Norway

Martin Hoelzle
World Glacier Monitoring Service, Department of Geosciences, University of Fribourg, Fribourg, Switzerland

Matthew J. Hoffmann
Los Alamos National Laboratory, Los Alamos, New Mexico, U.S.A.

Christian Huggel
Department of Geography, University of Zurich, Zurich, Switzerland

Angelika Humbert
Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany

Ricardo Jaña
Instituto Antártico Chileno, Punta Arenas, Chile; Fundación Centro de Estudios del Cuaternario, Punta Arenas, Chile

JIANG Zongli
Hunan University of Science and Technology, Hunan, China

Hester Jiskoot
Department of Geography, University of Lethbridge, Lethbridge, Alberta, Canada

Andreas Kääb
Department of Geosciences, University of Oslo, Blindern, Oslo, Norway
(*kaeaeb@geo.uio.no*)

Ulrich Kamp
Department of Geography, The University of Montana, Missoula, Montana, U.S.A.

Jeffrey S. Kargel
Department of Hydrology & Water Resources, College of Science, School of Earth & Environmental Sciences, The University of Arizona, Tucson, Arizona, U.S.A.; National Snow & Ice Data Center, University of Colorado, Boulder, Colorado, U.S.A.
(*kargel@hwr.arizona.edu*)

Siri Jodha S. Khalsa
National Snow & Ice Data Center, University of Colorado, Boulder, U.S.A.

Hugh H. Kieffer
Celestial Reasonings, Genoa, Nevada, U.S.A.

Joni L. Kincaid
Department of Geography, Texas A&M University, College Station, Texas, U.S.A.

Andrew Klein
Department of Geography, Texas A&M University, College Station, Texas, U.S.A.

Jack Kohler
Norwegian Polar Institute, Fram Center, Tromsø, Norway

Max König
Norwegian Polar Institute, Fram Center, Tromsø, Norway

Vladimir Konovalov
Russian Academy of Sciences, Moscow, Russia

Brandon S. Krumwiede
Department of Geography, The University of Montana, Missoula, Montana, U.S.A.

Anil V. Kulkarni
Indian Institute of Science, Bangalore, India

Chris F. Larsen
Geophysical Institute, University of Alaska,
Fairbanks, Alaska, U.S.A.

Gregory J. Leonard
Department of Hydrology & Water Resources,
University of Arizona, Tucson, Arizona, U.S.A.
(*gleonard@email.arizona.edu*)

LI Xin
Cold and Arid Regions Environmental and
Engineering Research Institute,
Chinese Academy of Sciences, Lanzhou, China

LI Zhen
Center for Earth Observation & Digital Earth,
Chinese Academy of Sciences, Beijing, China

Javier Lillo
Natural Área de Geología—ESCET, Universidad
Rey Juan Carlos, Móstoles, Madrid, Spain

LIU Shiyin
State Key Laboratory of Cryosphere Sciences,
Cold & Arid Regions of Environmental &
Engineering Research Institute, Chinese Academy
of Sciences, Lanzhou, China

Ivan Lopez
Natural Área de Geología—ESCET, Universidad
Rey Juan Carlos, Móstoles, Madrid, Spain

Thomas Loriaux
Centro de Estudios Científicos, Valdivia, Chile

LU Anxin
State Key Laboratory of Cryosphere Sciences,
Cold & Arid Regions of Environmental &
Engineering Research Institute, Chinese Academy
of Sciences, Lanzhou, China

Douglas Mair
School of Geosciences—Geography &
Environment, University of Aberdeen,
Scotland, U.K.

Sebastián Marinsek
División Glaciología, Instituto Antártico
Argentino, Buenos Aires, Argentina

Sandro Martinis
German Aerospace Center (DLR), German
Remote Sensing Data Center, Munich, Germany

Brian P. Menounos
Natural Resources & Environmental Studies
Institute, University of Northern British Columbia,
Prince George, British Columbia, Canada

Geir Moholdt
Scripps Institution of Oceanography, University of
California San Diego, La Jolla, California, U.S.A.

Bruce F. Molnia
U.S. Geological Survey, Reston, Virginia, U.S.A.

Pradeep Mool
International Center for Integrated Mountain
Development, Kathmandu, Nepal

Ulrich Münzer
Department of Earth & Environmental Sciences,
Section Geology, University of Munich,
Munich, Germany

Christopher Nuth
Department of Geosciences, University of Oslo,
Blindern, Oslo, Norway

Frank Paul
World Glacier Monitoring Service, Department of
Geography, University of Zurich, Zurich,
Switzerland
(*frank.paul@geo.uzh.ch*)

Massimo Pecci
Ente Italiano della Montagna, Roma, Italy

Rickard Pettersen
Department of Earth Sciences, University of
Uppsala, Uppsala, Sweden

Paolo Picca
Dipartimento di Energetica, Politecnico di Torino,
Turin, Italy

Mark Pleasants
Department of Geology, University of Dayton,
Dayton, Ohio, U.S.A.

Edward Pollock
Department of Earth Sciences, University of
Alberta, Edmonton, Alberta, Canada

Alberto Previti
Laboratorio di Ingegneria Nucleare di Montecuccolino, Alma Mater Studiorum, Università di Bologna, Bologna, Italy

Duncan J. Quincey
School of Geography, University of Leeds, Leeds, U.K.

Adina E. Racoviteanu
Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE), Saint-Martin-d'Hères, Grenoble, France

Bhaskar Ramachandran
NASA EOS LP DAAC, U.S. Geological Survey, Earth Resources Observation & Science Center, Sioux Falls, South Dakota, U.S.A.

Roberto Ranzi
Department of Civil Engineering, Architecture, Land, Environment and Department of Mathematics, University of Brescia, Brescia, Italy

Bruce H. Raup
National Snow & Ice Data Center, University of Colorado, Boulder, Colorado, U.S.A.
(*braup@nsidc.org*)

Andrés Rivera
Centro de Estudios Científicos (CECs), Valdivia, Chile;
Departamento de Geografía, Universidad de Chile, Santiago, Chile;
Departamento de Geofísica, Universidad de Chile, Santiago, Chile

José Luis Rodríguez
Centro de Estudios Científicos, Valdivia, Chile;
Universidad Católica de Temuco, Temuco, Chile;
Fundación Huilo Huilo,Las Condes, Santiago, Chile

Rakhshan Roohi
CAEWRI—National Agricultural Research Center, Islamabad, Pakistan;
Environmental Geoscience, Department of Agricultural Sciences, Faculty of Sciences, Technology and Engineering, La Trobe University, Victoria, Australia

Helmut Rott
Institute of Meteorology & Geophysics, University of Innsbruck, Innsbruck, Austria

Mehmet Akif Sarıkaya
Department of Geography, Fatih University, Istanbul, Turkey;
Eurasia Institute of Earth Science, Istanbul Technical University, Istanbul, Turkey

Erik Schiefer
Department of Geography, Planning, & Recreation, Northern Arizona University, Flagstaff, Arizona, U.S.A.

SHANGGUAN Donghui
State Key Laboratory of Cryosphere Sciences, Cold & Arid Regions Environmental & Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China

Martin Sharp
Department of Earth & Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada

Joseph M. Shea
Natural Resources & Environmental Studies Institute, University of Northern British Columbia, Prince George, British Columbia, Canada

John F. Shroder, Jr.
Department of Geography & Geology, University of Nebraska-Omaha, Omaha, Nebraska, U.S.A.

Oddur Sigurðsson
Icelandic Meteorological Office, Reykjavík, Iceland

Walter Silverio
Institute for Environmental Science, Climate Change & Climate Impact Group, University of Geneva, Switzerland

Pedro Skvarca
Glaciarium, Museo del Hielo Patagónico, El Calafate, Argentina

Claudio Smiraglia
Department of Earth Sciences, University of Milan, Milan, Italy

William A. Sneed
Climate Change Institute, University of Maine,
Orono, Maine, U.S.A.

I. Sossna
Department of Geography, University of Jena,
Jena, Germany

Leigh A. Stearns
Department of Geology, University of Kansas,
Lawrence, Kansas, U.S.A.

Ahmet Emre Tekeli
Civil Engineering Department, King Saud
University, Riyadh, Saudi Arabia;
Civil Engineering Department, Zirve University,
Gaziantep, Turkey;
Remote Sensing Division, Turkish State
Meteorological Service, Ankara, Turkey

Kristina Thorneykroft
Department of Geology, Portland State University,
Portland, Oregon, U.S.A.

Thierry Toutin
Natural Resources Canada, Ottawa,
Ontario, Canada

Michael Walther
MOLARE Research Center for Climate &
Landscape Studies, National University of
Mongolia, Ulaanbaatar, Mongolia

Libo Wang
Climate Research Division, Atmospheric Science &
Technology Directorate, Environment Canada,
Toronto, Ontario, Canada

WANG Xin
School of Architecture & Urban Planning, Hunan
University of Science and Technology,
Xiangtan, China

WEI Junfeng
State Key Laboratory of Cryosphere Sciences,
Cold & Arid Regions of Environmental &
Engineering Research Institute, Chinese Academy
of Sciences, Lanzhou, China

Brandon J. Weihs
Department of Geography, Kansas State
University, Manhattan, Kansas, U.S.A.

Anja Wendt
Centro de Estudios Científicos (CECs),
Valdivia, Chile

Roger D. Wheate
Natural Resources & Environmental Studies
Institute, University of Northern British Columbia,
Prince George, British Columbia, Canada

Richard S. Williams, Jr.
Woods Hole Research Center, Woods Hole,
Massachusetts, U.S.A.

Scott N. Williamson
Department of Biological Sciences, University of
Alberta, Edmonton, Alberta, Canada

Cláudio Wilson Mendes Júnior
Instituto Nacional de Ciência e Tecnologia
da Criosfera, Laboratório de Monitoramento da
Criosfera, Instituto de Ciências Humanas e da
Informação, Universidade Federal do Rio Grande,
Rio Grande, Brazil;
Instituto Nacional de Ciência e Tecnologia da
Criosfera, Centro Polar e Climático, Universidade
Federal do Rio Grande do Sul, Porto Alegre, Brazil

Philip Wilson
Parks Canada—Nahanni National Park &
Reserve, Fort Simpson, Northwest Territories,
Canada

Steve Wilson
Department of Geology, Portland State University,
Portland, Oregon, U.S.A.

David F.G. Wolfe
GLIMS Alaska Regional Center Steward,
Anchorage, Alaska, U.S.A.

Gabriel J. Wolken
Department of Earth & Atmospheric Sciences,
University of Alberta, Edmonton, Alberta, Canada

WU Lizong
Cold & Arid Regions of Environmental &
Engineering Research Institute, Chinese Academy
of Sciences, Lanzhou, China

Faye Wyatt
Department of Earth & Atmospheric Sciences,
University of Alberta, Edmonton, Alberta, Canada

XU Junli
State Key Laboratory of Cryosphere Sciences, Cold & Arid Regions of Environmental & Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China

YAO Xiaojun
State Key Laboratory of Cryosphere Sciences, Cold & Arid Regions of Environmental & Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China; Geography & Environment College, Northwest Normal University, Lanzhou, China

YE Baisheng
State Key Laboratory of Cryosphere Sciences, Cold & Arid Regions of Environmental & Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China

Rodrigo Zamora
Centro de Estudios Científicos (CECs), Valdivia, Chile

Michael Zemp
World Glacier Monitoring Service, Department of Geography, University of Zurich, Zurich, Switzerland

Pablo Zenteno
Centro de Estudios Científicos (CECs), Valdivia, Chile

ZHANG Shiqiang
State Key Laboratory of Cryosphere Sciences, Cold & Arid Regions of Environmental & Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China

Foreword

The origin and development of GLIMS (a personal perspective)

by Hugh H. Kieffer, Celestial Reasonings, Genoa, Nevada

I was a young glaciologist once, working for Barkley Kamb and Ron Shreve on the Blue Glacier (WA, USA) and for Mario Giovinetto in Antarctica in the early 1960s. After a 25-year diversion to Mars and its polar caps, I returned to work with terrestrial spacecraft, and again turned my attention to glaciers. I was then at the Astrogeology Branch of the U.S. Geological Survey in Flagstaff, AZ.

In 1988, a group of us led by Anne Kahle (who eventually became the first U.S. ASTER Science Team Leader) proposed to NASA a combined infrared multi-band thermal mapper with an embedded spot infrared spectrometer. This instrument was not selected. However, our team was chosen to join with a team from Japan that would provide to NASA an instrument combining three imaging subsystems: a 3-band visible and near-IR (VNIR) 15 m resolution subsystem with 1-band stereo, a 6-band short-wave IR (SWIR) subsystem with 30 m resolution, and a 5-band thermal-IR (TIR) subsystem with 90 m resolution. All of the US team members had to write proposals for what science they would do with this huge instrument; two of my objectives were Monitoring polar outflow-glacier velocities, and Observations of glacier advance or retreat. This instrument became ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) on the first EOS platform, Terra, launched in December 1999. An important capability was that the VNIR subsystem could point 24° to either side, allowing imaging to 85° latitude, considerably increasing coverage of the trans-Antarctic mountain range beyond that accessible with the Landsat satellites. Although the SWIR subsystem ceased operation in 2008, the VNIR and TIR subsystems continue to function in their old age.

The VNIR color could easily distinguish ice and snow from rock and vegetation. The SWIR allowed estimation of grain size and clear distinction of snow from ice, and the TIR could measure surface temperature. Not recognized at that time was the ability to identify sediment load in glacier-surface pools, the ability of stereoscopic imaging to produce DEMs that can help to discern changes in glacier thickness in optimum circumstances, multitemporal imaging that can be used not just to map glacier flow speeds but areas of accelerating and decelerating ice, and VNIR data that can be used to assess growth of vegetation on recently emplaced glacial deposits.

The ASTER VNIR instrument was clearly capable of supporting a 15 m resolution inventory of the world's glaciers; however, a few political and technical steps were involved, each a challenge: (1) getting acceptance of glacier monitoring as an objective of the bi-national ASTER investigation; (2) establishing a method of efficiently scheduling ASTER observations of glaciers; (3) curating the resulting imagery and extracting the glacier information.

The first was accomplished by presentations at the ASTER Science Team meetings, held twice per year. However, the activity needed a name. Having regretted for decades selection of an unpronounceable acronym for an instrument, I insisted that the initials for the name of our dream be a pronounceable acronym, and eventually we settled on GLIMS (Global Land Ice Measurements from Space). *Glim* is an archaic Scottish term that means "a passing look; a glimpse; as much as is seen at a glance," and that seemed appropriate, given our understanding of the effect of global warming.

The second step required considerable iteration with the ASTER group in Japan that was developing the command dictionary and the massive ground data system; the huge scope derived from the ASTER objective to cover all land area on Earth with 15 m stereo with daytime coverage, and much of it at night. GLIMS hoped for annual, non-cloudy coverage in late summer for mountain glaciers and well-lit margins of the polar ice sheets. Anticipating significant cloud cover over glaciers, successful acquisition would depend to some extent on automated rescheduling if images were classified as cloudy. However, we did not expect that the automated cloud coverage algorithm would work well over glaciers, and indeed clouds have remained a challenge. GLIMS did not initially target the interiors of ice sheets.

While the first two steps could be done by a few people, the third could only be accomplished by a large organization, preferably involving people familiar with the glaciers and terrain. From this came the concept of Regional Centers (RCs) and Stewards. RCs were intended to have both data analysis and organizational responsibilities. My experience in large organizations led me to believe that organizations with large "fan-out" factors were difficult to manage; hence, we initially envisioned about a dozen RCs covering geographically contiguous regions. The number has since grown to about 30. RCs could involve as many Stewards as they wished, with a Steward having responsibility for a sub-section of the region, down to an individual glacier. The key concept was that the GLIMS leadership did not have any direct interface responsibility with Stewards; Stewards received guidance from and delivered their products to the RCs. The RCs were responsible for initial quality checks on the derived glacier information for their region, including material from their Stewards. A list of the current RCs and Stewards is at *http://www.glims.org/glims/nsidc_rc_table_public.php*

The new GLIMS group would complement two major existing activities; the venerable World Glacier Monitoring Service (WGMS) (1894+) with emphasis on precision field measurements of several hundred glaciers, and the multi-volume USGS *Satellite Image Atlas of Glaciers of the World* (Williams and Ferrigno, 1988) with comprehensive discussion but lacking a digital database.

In June 1994, while on a personal trip to Austria and Switzerland, I visited Michael Kuhn at the University of Innsbruck and Wilfried Haeberli at ETH Zurich to present the concept of satellite-based glacier monitoring. My reception was polite, but it took many discussions and years of slowly converging interests until GLIMS and WGMS eventually became closely integrated. Today GLIMS, WGMS, and the U.S. National Snow and Ice Data Center constitute the Global Terrestrial Network for Glaciers (GTN-G, *http://www.gtn-g.org*). Although ground-based observations had been made for decades to centuries, the total number of glaciers monitored was small. When glacier terminus position change was considered in light of the local climate, as in the seminal paper by J. Oerlemans (1994), a consistent warming rate emerged. However, a globally comprehensive approach could better define regional variations, help assess the role of glacier response time on measured variability, and separate short-term effects from the secular influence of climate change,

On August 9, 1994, at the IGS International Symposium on the Role of the Cryosphere in Global Change held at Columbus, Ohio, U.S.A., Jeff Kargel and I made the first open presentation of the GLIMS concept. Fifteen years later, GLIMS had a major role in the world's integrated approach to monitoring glaciers; see *http://www.fao.org/gtos/doc/ECVs/T06/T06.pdf* (2009). GLIMS was started on adrenaline at the USGS in Flagstaff; the only funding was through my team membership on ASTER. Over two years the effort grew to a maximum of about two funded positions. There was a tiny fraction of myself; a fraction of Jeff Kargel, who was a planetary geomorphologist and geochemist, then working on Martian glacial geomorphology and Earth analogs; most of Bruce Raup (see below), who had some other ASTER tasks; and most of Rick Wessels, a remote-sensing volcanologist. All but me are still involved in GLIMS!

In the summer of 1995 I emailed to many colleagues an announcement of a position for someone with an engineering background (so they would be familiar with the construction and capabilities of the ASTER instrument), who could work on development of software for measurements of glacier flow and would be skillful in interacting with the Japanese ASTER Team. Astoundingly, I had an applicant—Bruce Raup—with a B.S. degree in engineering physics who had worked for a Japanese engineering firm, had just finished a M.S. thesis in finite-element modeling of glacier flow, and was fluent in several computer languages as well as written and spoken Japanese (having studied in Japan for two years). Bruce worked in my group for four years and is still a prominent figure in GLIMS.

While Jeff and I worked on establishing the GLIMS organization and defining measurement approaches, Bruce and Rick developed the concepts and software for scheduling ASTER coverage and processing the images into a glacier outline database.

The technical objective was to make full use of modern satellite and computer capabilities. Because of the initial funding source, the data-handling activity concentrated on ASTER. However, our plans had an eye toward later inclusion of data from other instruments, both similar to ASTER (e.g., the Landsat series) and other techniques such as interferometric radar and laser altimetry.

The data formats and data-flow process were refined by extensive interaction with interested glaciologists and database technicians. Once the GLIMS organizational structure and initial Regional Centers were established, development and feedback on the technical aspects progressed rapidly.

Key concepts related to data extraction and storage were: (1) All the products must be fully digital and in a consistent format. (2) The format must support automated comparisons over time to quantify change. (3) The database should be available to anyone.

A corollary was a requirement for uniform quality control on the material entering the GLIMS database. With an objective of addressing the estimated 170,000 glaciers, the accurate extraction of margins, termini, divides, source areas, and other attributes needed support of powerful and reliable software. Bruce Raup has led the integration of these requirements into the development of GLIMSView, and most importantly, the digital glacier database (initially developed at USGS, but now hosted by the National Snow and Ice Data Center).

In the 1990s, the environment for acceptance of GLIMS was marginal. Global warming was not widely accepted (at least in the U.S., and certainly not in Washington, D.C.); the relation of glaciers to climate was conjectural (doubters would cite the opposing behavior of adjacent glaciers in Alaska, for example); most glaciologists worked in the field, but not with remote sensing; the emphasis was on mass balance (very difficult then to measure remotely), not terminus positions; the WGMS concentrated on a modest number of glaciers that were intensely studied; regional inventory activity was largely outlines on analog maps (e.g., Canada and the eastern Himalaya). At that time, GLIMS was conceived mainly around terminus and area fluctuations, believing then that we could not remotely sense changes in glacier thickness (not from ASTER, at least).

It is challenging to obtain funding for an activity that crosses agency lines, and at that time it seemed that we needed several agencies to provide the needed financial support. This was certainly the case for GLIMS, with NASA responsible for ASTER and other EOS instruments, NOAA addressing climate monitoring, the USGS with a small glacier-monitoring program and home of the GLIMS principals, and the National Science Foundation that supported much of the basic climate research. Commonly in a discussion with one of these, they would say, “but this is agency X’s area”. To address this ubiquitous redirection, I arranged a joint meeting with representatives of NASA, NOAA, USGS, and NSF. This meeting raised awareness of the GLIMS objectives and the inter-agency interests, but did not immediately generate fiscal support. GLIMS toddled along on ASTER team-member funding for nearly a decade. There was, however, a general interest in the science community and we began organization of the RCs, with a mutual faith that our various governments and institutions would ultimately recognize the importance and efficacy of global coordination. The early and continued involvement of Andy Kääb, Michael Bishop, and others provided inspiration, perspective, and technical prowess, and some essential humor.

GLIMS international organization also faced serious challenges due to political dividing lines. The original concept was for a physical geographic division of regional centers. However, the case of the Alps proved an initial organizational challenge, where each participating nation had its own funding agencies, and each nation had its own significant history of interest in its glaciers dating decades (or more than a century) before GLIMS. The European Union had just been formed (November 1, 1993) and this predated the Euro-zone (January 1, 1999). This “first among equals” situation was resolved by the willingness of an Italian hydrologist fluent in French and German who was working in

Switzerland, Paolo Burlando. However, eventually this arrangement dissolved, and separate regional centers were defined for each Alpine nation. Similarly, other challenges loomed for Scandinavia, the Himalayan region, and others. Some were successfully integrated across national borders, but most were not.

GLIMS workshops began in 1999 and were held about once per year, commonly in conjunction with IGS or other scientific society meetings, and intentionally geographically diverse (a list is at *http://www.glims.org/Workshops/*).

Since my retirement in 2003, GLIMS activity has flourished. Database, quality control, and technical interaction with the RCs has been driven mainly by NSIDC (University of Colorado), with NASA funding to Richard Armstrong. Some algorithm development and applications, and RC and workshop organization has taken place at the University of Arizona, where Kargel has operated with NASA ASTER Science Team support since 2005. Other NASA funding has supported several other U.S. GLIMS investigators; foreign regional centers are supported by their own, mainly national, funding sources. The Regional Centers (together with their Stewards) remain the main source of glacier analysis, as well as a prodigious family of innovators for GLIMS.

The scientific value of GLIMS has become widely recognized. I am pleased to have been part of the origin of GLIMS and gratified by its growth, which is due to the efforts of many dedicated people around the world. If only the glaciers could do so well. . . .

Thus endeth my story; all the rest is in the pages that follow.

REFERENCES

Oerlemans, J. (1994) Quantifying global warming from the retreat of glaciers. *Science*, **264**, 243–245.

Williams, R.S., Jr., and Ferrigno, J.G. (Eds.) (1988+), *Satellite Images Atlas of Glaciers of the Work* (USGS Prof. Paper 1386, 11 volumes, A–K). Available at *http://pubs.usgs.gov/pp/p1386/*

Acknowledgments

First, the authors are grateful to the global glaciology research community for their cooperative spirit that has made GLIMS a successful project. We also thank many people who have been important in supporting GLIMS including those at ASTER Mission Operations, those helping to bring this book project through to completion, or in otherwise lending support to GLIMS through the years. At Praxis and Springer we are grateful to Philippe Blondel, Clive Horwood, Janet Sterritt, and Neil Shuttlewood for their guidance and dedication to this book project. Thanks also to Jim Wilkie for producing a spectacular cover design. We greatly appreciate the work of Kate Taralova for creating a wiki site that was crucial early in the book project. We wish to acknowledge Tom Wagner, Jared Entin, Waleed Abdalati, Seelye Martin, Cerese Albers, Dan Irwin, Ashutosh Limaye, Nancy Searby, and Woody Turner at NASA for having provided a support base and ASTER data access; and Michael Abrams, Leon Maldonado, Anne Kahle at NASA/JPL on ASTER Mission Operations; and Yasushi Yamaguchi, Hiroyuki Fujisada, Kohei Arai, Isao Sato on the Japan side of the U.S.–Japan Terra/ASTER program. We are grateful as well to ESA for having supported GLIMS through the GlobGlacier, SPOT-IPY, and other programs; and to NASA, ESA, ISRO, and other space agencies for a long succession of capable, productive, and essential Earth-observing satellites; and to USGS for having made possible the inception of GLIMS 20 years ago.

Jeff Kargel thanks NASA, USAID, and the peer community and taxpayers for having sustained Jeff's work in GLIMS through a succession of grants through the NASA IPY, Science of Terra and Aqua, SERVIR Applied Sciences Team, and Climbers' Science programs. Specifically, Jeff thanks Lana Lightle, Michael Cote, and Alton Byers with the USAID Climbers' Science Program for their enthusiastic support of field-based research. He also extends gratitude to Rick Wessels, who was important in the early operational phase of GLIMS, and particularly Greg Leonard who has served the GLIMS project so well for the past five years. Jeff also thanks his family, including now-grown children, and his wife Huong (“Bé”), for her enduring patience and support. Jeff recognizes that the positive impact that the editors can hope to have on the world begins with the positive impact our families have on us.

Gregory Leonard is highly appreciative for the support of GLIMS work he has received through a series of grants from NASA and USAID that includes the NASA IPY, the Science of Terra and Aqua, SERVIR Applied Sciences Team, and the Climber's Science programs. He is incredibly thankful to his coeditors, Michael Bishop, Andy Kääb, Bruce Raup, and especially Jeff Kargel, all of whom continue to inspire him to perceive glaciers in new ways. Greg is most grateful for the support of his family and friends who also believe with him in the importance of scientific investigation, and share in the joy of exploring the natural world.

Michael Bishop thanks NASA, Hugh Kieffer, and Jeff Kargel for establishing the GLIMS project. He would also like to thank the individuals who assisted in the analysis of data for studying the glaciers in Afghanistan and Pakistan. Special thanks are extended to Gregory Leonard, Andrew B.G. Bush, Umesh Haritashya, Jeffrey Olsenholler, and John F. Shroder, Jr. Furthermore, thanks are extended to his family for enduring the Friday afternoon teleconferences for years and years and years.

Andreas Kääb expresses gratitude to ESA for support on the GLIMS and related glacier monitoring projects through the GlobGlacier and Glaciers_cci contracts, and to the European Research Council through its Advanced Grant. Without Wilfried Haeberli, Hugh Kieffer and Jeff Kargel, Andy would not have found his way into satellite-based glacier monitoring. Special thanks from Andy go to his wife Regula and the children for their emotional support and patience with the book project.

Bruce Raup is grateful to NASA for several grants, including from the REASoN and ACCESS programs. Many people at NSIDC have been extremely helpful and supportive. Richard Armstrong, in particular, has been the strongest champion for GLIMS and PI on most of the GLIMS-related grants. Bruce is also thankful to the NSIDC Distributed Active Archive Center (DAAC) for picking up the GLIMS Glacier Database for their data portfolio. Lastly, Bruce is thankful for the support and patience of his family.

Online supplemental material

The Online Supplemental materials listed below are arranged by chapter and number of supplements per chapter. These materials represent: (i) full figures, figure panels, and plots from the chapters that can be viewed as higher resolution files or otherwise as larger images to observe details that might be obscured or difficult to discern in the book, (ii) additional material to support analysis and conclusions reported within the chapters, (iii) additional analyses that expand upon research presented within the chapter. With the exception of figures and plots that appear in the chapters of this book, all other auxillary supplemental material is not peer reviewed.

Chapter	*No. of online supplements*
01—Introduction: Global glacier monitoring	3
02—Foundations of glacier remote sensing	0
03—Radiative transfer modeling in the cryosphere	8
04—Multispectral glacier mapping	10
05—Digital terrain and glacier topographic modeling	3
06—ASTER datasets for glacier monitoring	1
07—Quality in the GLIMS Database	6
08—Greenland	3
09—Canadian Arctic	7

Chapter	*No. of online supplements*
10—Svalbard Glacier Database	5
11—Alaska: Southwest glaciers	6
12—Alaska: Glacier-dammed lakes	14
13—Alaska: Chugach glaciers and lakes	22
14—Canadian Cordillera	6
15—Hoodoo Mountain, British Columbia, Canada	8
16—Nahanni National Park Reserve, Northwest Territories, Canada	4
17—U.S. Cordillera	10
18—Iceland	1
19—Norway	2