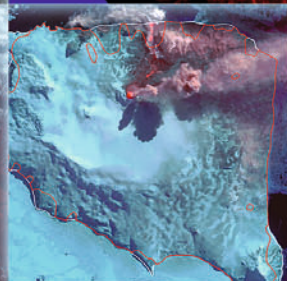
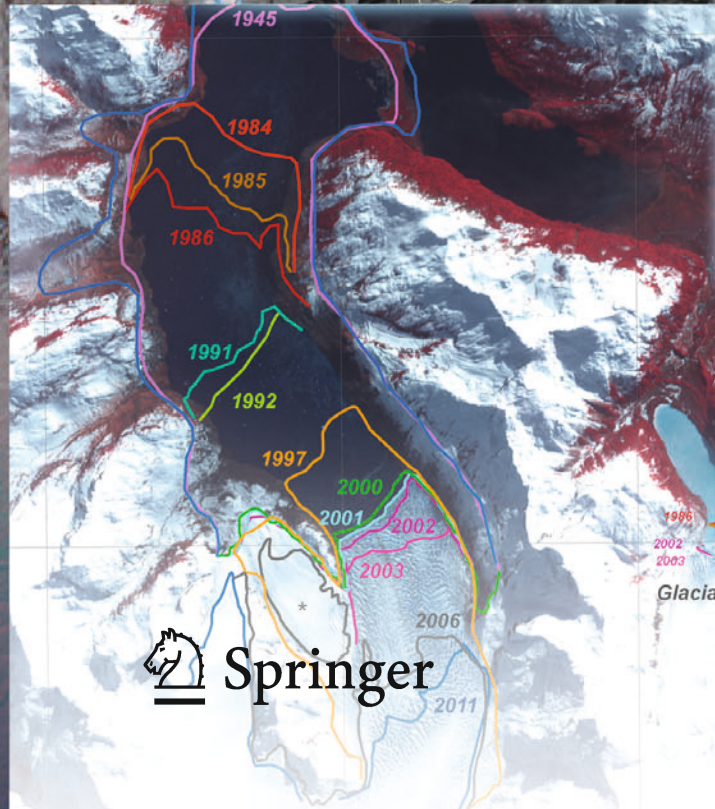
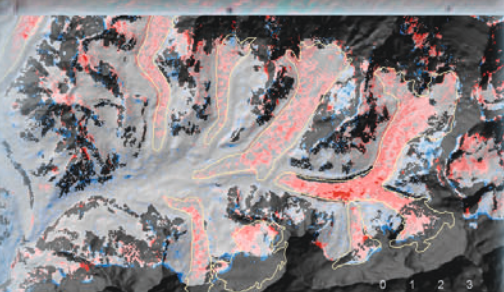
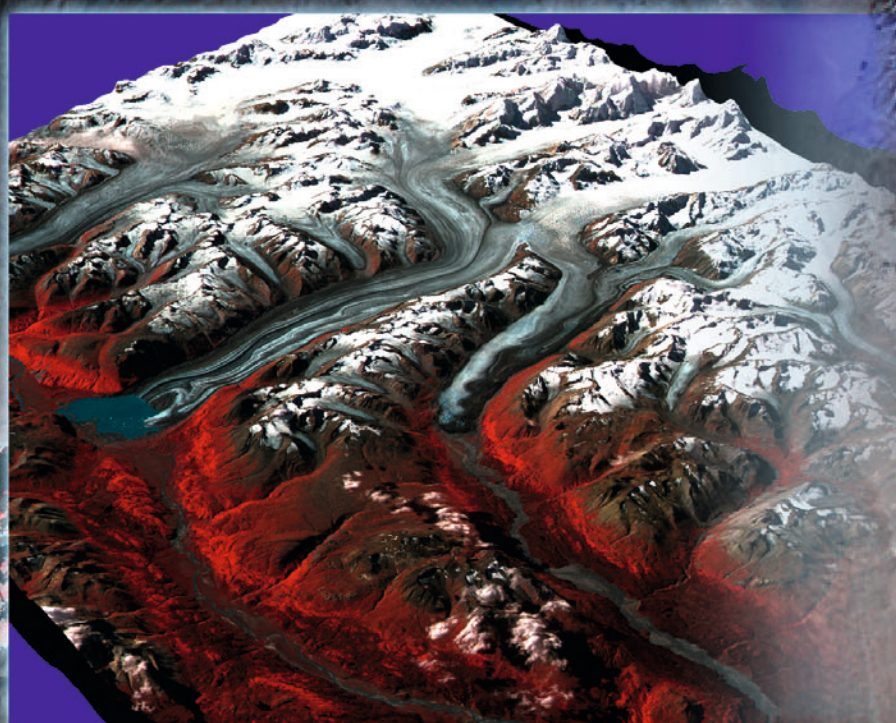


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# Global Land Ice Measurements from Space

Jeffrey S. Kargel  
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Editors

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PRAXIS 

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## 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.

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## 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, multi-temporal 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](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 outlined 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.

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## 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 auxiliary supplemental material is not peer reviewed.

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