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The GLIMS geospatial glacier database: A new tool for studying glacier change ☆

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Abstract

The Global Land Ice Measurement from Space (GLIMS) project is a cooperative effort of over sixty institutions world-wide with the goal of inventorying a majority of the world's estimated 160 000 glaciers. Each institution (called a Regional Center, or RC) oversees the analysis of satellite imagery for a particular region containing glacier ice. Data received by the GLIMS team at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado are ingested into a spatially-enabled database (PostGIS) and made available via a website featuring an interactive map, and a Web-Mapping Service (WMS). The WMS, an Open Geospatial Consortium (OGC)-compliant web interface, makes GLIMS glacier data available to other data servers.

The GLIMS Glacier Database is accessible on the World Wide Web at "http://nsidc.org/glims/". There, users can browse custom maps, display various data layers, query information within the GLIMS database, and download query results in different GIS-compatible formats. Map layers include glacier outlines, footprints of ASTER satellite optical images acquired over glaciers, and Regional Center information. The glacier and ASTER footprint layers may be queried for scalar attribute data, such as analyst name and date of contribution for glacier data, and acquisition time and browse imagery for the ASTER footprint layer.

We present an example analysis of change in Cordillera Blanca glaciers, as determined by comparing data in the GLIMS Glacier Database to historical data. Results show marked changes in that system over the last 30 years, but also point out the need for establishing clear protocols for glacier monitoring from remote-sensing data.

Keywords: glacier monitoring; glacier change; Cordillera Blanca; open source GIS

1. Introduction

Glaciers, bodies of ice that persist for years, assume a size and flow rate that are in balance with local climate. Changes in climate therefore induce changes in glaciers, making them sensitive and easily observed indicators of climate change (Haeberli, 2004). Several international programs are focused on monitoring glacier change. The World Glacier Monitoring Service (WGMS) was established in 1986 for the collection of standardized glacier observations from around the world. Since then, glaciers have been made part of the Global Climate Observing System (GCOS) and the Global Hierarchical

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Observing Strategy (GHOST), programs established by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC), the United Nations Environment Programme (UNEP) and the International Council of Scientific Unions (ICSU) (Haeberli, 2004). The project described in this paper, Global Land Ice Measurements from Space (GLIMS), is meant to fit into these programs and extend existing glacier inventories.

There are an estimated 160 000 glaciers on Earth (Meier and Bahr, 1996). Small numbers of glaciers have been monitored through field measurements for decades (Braithwaite, 2002), and a handful of inventories have been compiled, most of them at no larger than regional scales. The WGMS compiled the World Glacier Inventory (WGI, IAHS[ICSI]-UNEP-UNESCO, 1989; Haeberli, 1998), and this effort represents the first real attempt at an inventory at the global scale. While the WGI is a valuable database that continues to be used to study changes in the cryosphere, its design was limited to the technology of its time, and it was not designed to store certain kinds of information valuable to studies of glacier change, such as glacier outlines and hypsometry. The advent of plentiful satellite imagery, widely available sophisticated image processing software, and inexpensive computers with large amounts of data storage has led to the formation of GLIMS, which aims to build on and improve the world inventory of glacier data.

The goal of GLIMS is to acquire satellite multispectral images of the world's glaciers and analyze them for glacier extent and changes, and to understand these change data in terms of climatic and other forcings (Kieffer et al., 2000; http://www.glims.org/). The scope of GLIMS requires an international consortium, which currently involves researchers from 27 countries. GLIMS is organized into a system of Regional Centers (RCs), which divides the world's glacierized areas into manageable subregions, based mostly on political boundaries. The RCs include a network of collaborating Stewards, who may be responsible, for instance, for the analysis of a single glacier or may take on broader roles. RCs are provided with "GLIMSView", a cross-platform computer application specifically developed to analyze satellite imagery such as from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Landsat, digitize glacier outlines, attach GLIMS-specific metadata, and package the data for import into the GLIMS database.

GLIMS was initiated and originally coordinated by the U.S. Geological Survey (Flagstaff, Arizona), and is currently coordinated by the University of Arizona (Tucson). GLIMS originated as an ASTER Science Team effort, and ASTER imagery is ideal in many regards to fulfill the goals of GLIMS, although other data, such as Landsat ETM+, older Landsat, SPOT, SAR imaging, and historic maps and air photos help to fill gaps, extend coverage over several decades, and provide important complementary observations. As an ASTER Science Team activity we have submitted ASTER imaging acquisition requests to the ASTER Ground Data System for (nominally) annual image acquisitions of imagery over all glaciers, ice caps, and ice sheet margins on Earth, with requested imaging season and instrument gain settings optimized for glaciers (Raup et al., 2000).

The main product of the GLIMS project is the GLIMS Glacier Database, a spatio-temporal database storing glacier outlines and a variety of metadata, including information on the analyst and processing techniques used, scalar data about the glacier including width, length, and speed, and related literature references. The database was designed and implemented at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, USA, and is being populated with data as Regional Centers complete their analyses and submit their data. When fully populated, this database will enable studies previously impossible, such as determining global patterns of glacier changes, global trends in glacier-related hazards, or global impacts of glacier changes on humans. Additionally, the GLIMS Glacier Database will facilitate local and regional studies of glacier changes, as illustrated in the example application below.

This paper describes how the GLIMS Glacier Database serves as both an extension of the World Glacier Inventory (and snapshot of global glacier distribution), and as the basis for monitoring glacier changes through time. As the spatial coverage in the database becomes more complete, global investigations into topics such as glacier scaling statistics (cf. Meier and Bahr, 1996) and global water resource issues become possible. The span of multi-temporal data will grow as updated glacier information is derived from future satellite imagery, and as past information based on maps is incorporated. We also present an example application of glacier change measurement, and use this as an illustration of the difficulties of disparate and inconsistent glacier inventories – difficulties that GLIMS hopes to alleviate.

2. The GLIMS glacier database

The GLIMS Glacier Database (Fig. 1) has been designed to store geospatial information about glaciers. We faced several challenges in the design of this database. These included representation of time-varying information about a set of objects, which in some cases have tree-like relationships between them. Also, the

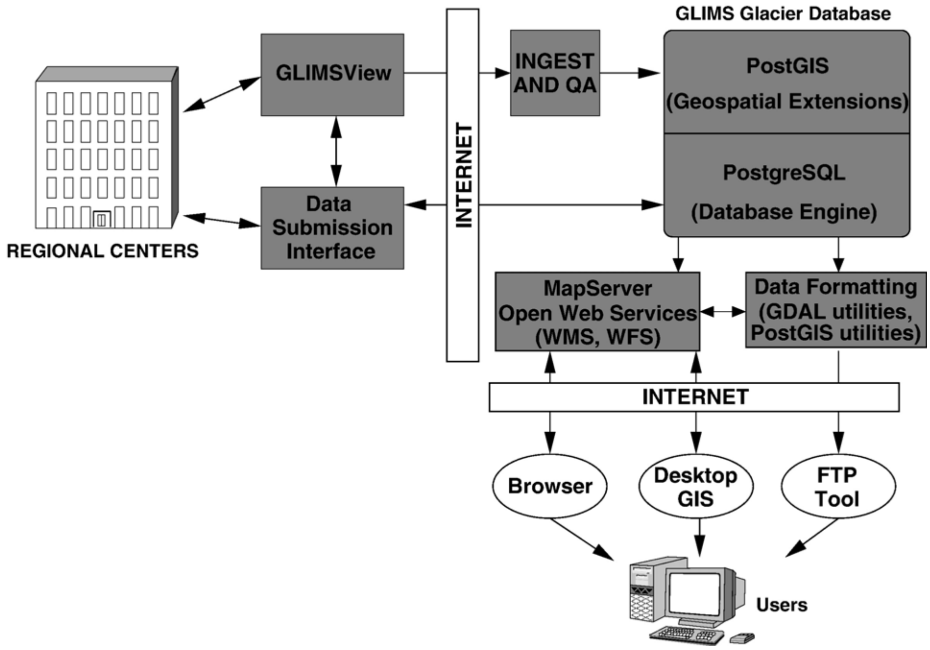

Fig. 1. System architecture of the GLIMS Glacier Database and its interfaces.

analyses producing this information are performed using a variety of input sources (imagery from various satellites, air photos, and maps) and methods including both automatic algorithms and manual interpretation. Since GLIMS glacier data come from many researchers from around the world, a wealth of metadata about the analyses and about the analyst must be accommodated.

Table 1 lists the major tables in the GLIMS Glacier Database. The two main tables are called Glacier_Static and Glacier_Dynamic. The first stores static (normally unchanging) information, such as the glacier's name and location. The second stores measured attributes of a glacier that are associated with a specific time, for example its length, width, speed, and outline. Other tables store related information such as image and map metadata, browse imagery and other raster data, glacier hypsometry, information about GLIMS institutions and data contributors, and relevant literature references. The Glacier_Dynamic table stores a time stamp identifying the time represented by the information. As a result, the database can store a time series of glacier data that can be analyzed for trends, and is thus an effective tool for detection of changes in Earth's cryosphere and climate.

Glaciers are identified in the database using an ID composed from its longitude and latitude (WGS-84 datum), such as 'G225691E58672N' for the Taku Glacier in Alaska. With this scheme, analysts can assign IDs without fear of their assignments conflicting with those of other analysts. The use of three decimal places for the coordinates in the ID provides enough precision to avoid conflicts between IDs of adjacent glaciers in all known cases. Glacier outlines are stored in the database in longitude/latitude/WGS-84 coordinates. By treating each glacier individually, glacier-by-glacier comparisons of measurements over time can be made.

As a glacier retreats, it can separate into two or more parts. In order to keep track of the relationship between these smaller remnants and the larger glacier from which they formed, the Glacier_Static table contains a field that can store the ID of a glacier's parent ice mass. A remnant would be given a new glacier ID, and the ID of its parent is stored. This scheme for representing parent–child relationships between records in the database is

Table 1
List of main tables in the GLIMS glacier database

Main tables in the GLIMS glacier database	
Table name	**Description**
Glacier_Static	Non- or little-changing information about a glacier
Glacier_Dynamic	Snapshots of glacier state
Instrument/Image/Band	Information about images and sensors
Reference_Document	Links to journal articles, maps, etc.
Regional_Centers/People	Information regarding data, originator
Segments	Glacier outlines, centerlines, snow lines, etc.
Point_Measurement	Geolocated measurements such as debris thickness
Area_Histogram	Area-elevation histogram data

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also useful in the case when a large ice mass is initially analyzed and entered into the database as one glacier, and then it is subsequently analyzed in more detail, where different parts of it are identified as glaciers in their own right and given their own glacier IDs. Using the "parent ice mass" field, the continuity of analyses stretching over time and levels of detail is preserved, such that an analyst can later repeat the original analysis or update it, and thus validate the earlier work or produce a time series using the same glacier definitions.

The GLIMS Glacier Database is designed to be a logical extension of the World Glacier Inventory of the WGMS. The WGI is a one-time view of the state of glaciers, and holds data on approximately 71 000 glaciers, about 44% of the estimated global total. Each glacier snapshot in the Glacier_Dynamic table of the GLIMS database can store the full complement of WGMS-defined glacier characteristics used in the WGI, including such parameters as primary glacier classification, glacier form, and dominant mass source. The WGMS glacier ID is stored in the Glacier_Static table, linking the two databases. The GLIMS Glacier Database therefore is extending the WGI by adding multiple snapshots over time, by increasing the number of glaciers covered, and by storing full glacier outlines, rather than just point locations. Also available are glacier outlines from the Digital Chart of the World (DCW) (ESRI, 1992), and comparisons with the ASTER-derived GLIMS glacier outlines that have so far been ingested into the GLIMS database illustrates the marked improvement that GLIMS glacier outlines represent compared to DCW data.

Many GLIMS colleagues wish to contribute their data as it is produced, but also need time to prepare publications before the data are made publicly available. The database allows for an embargo period to be specified at the time data are contributed, and a date is stored indicating the time before which those data records will not be distributed to the public. This allows the data transfer to NSIDC to be performed while data processing details are still fresh in the minds of the providers, yet protects the needs of the researchers involved. When publicly-available data are downloaded, metadata including the name of the data provider and appropriate citation information are included.

Special attention is paid to storing estimated errors in position for glacier outlines. The Glacier_Dynamic table contains fields for both "local" uncertainty in vertex position (related to the precision of the measurements) and "global" uncertainty (related to geolocation accuracy). These fields are required; no data set is accepted if it does not include these values.

NSIDC has implemented the GLIMS Glacier Database using the relational database engine PostgreSQL, which has been augmented with geospatial data types and functionality provided by PostGIS. PostGIS provides many functions for performing sophisticated geospatial queries and operations. Because the whole database is implemented with Open Source software, the framework is freely sharable with other GLIMS colleagues.

The results of glacier analysis at the various Regional Centers are sent to the National Snow and Ice Data Center in Boulder, Colorado, USA. The submission process is described in the Next section.

As of the end of 2005, the database contains outlines and metadata on approximately 50 000 glaciers, contributed from eleven GLIMS institutions. This includes glaciers in the European Alps, Patagonia, Chilean volcanoes, Caucasus, Tien Shan, Sweden, Cordillera Blanca (Peru), China, and Alaska. The database is already useful as a repository of information on climate-related changes in the cryosphere, and as the data set becomes increasingly complete in the coming years, more complex spatial and temporal analysis will become easier.

3. Interfaces

NSIDC has created a map-based World Wide Web interface to the database, accessible at http://nsidc.org/glims/. An example screen is depicted in Fig. 2. The system architecture of the database and its interfaces are shown in Fig. 1. The website allows people to view interactive maps in a browser by selecting desired features, zooming and panning, and querying map objects for their attribute data. Table 2 lists the features available for display in the map. The main mappable feature, or map "layer", consists of the GLIMS glacier outlines, centerlines, and snow lines. Two layers depict information about the GLIMS project itself: Regional Center outlines and GLIMS institutions. Another layer contains metadata about ASTER imagery acquired over glacierized regions. Other supporting data layers include the high-resolution imagery from which the glacier analyses were done ("Source Images"), the glacier layer from the Digital Chart of the World, the World Glacier Inventory, country borders, and a MODIS global mosaic.

The user can search for subsets of glacier and supporting data, applying constraints on time range or geographic area, and the results are presented in a map image, together with a table of selected attribute data. There is a separate form-based interface for constraining the search by scalar fields such as glacier classification, glacier length, or speed. The results of queries made

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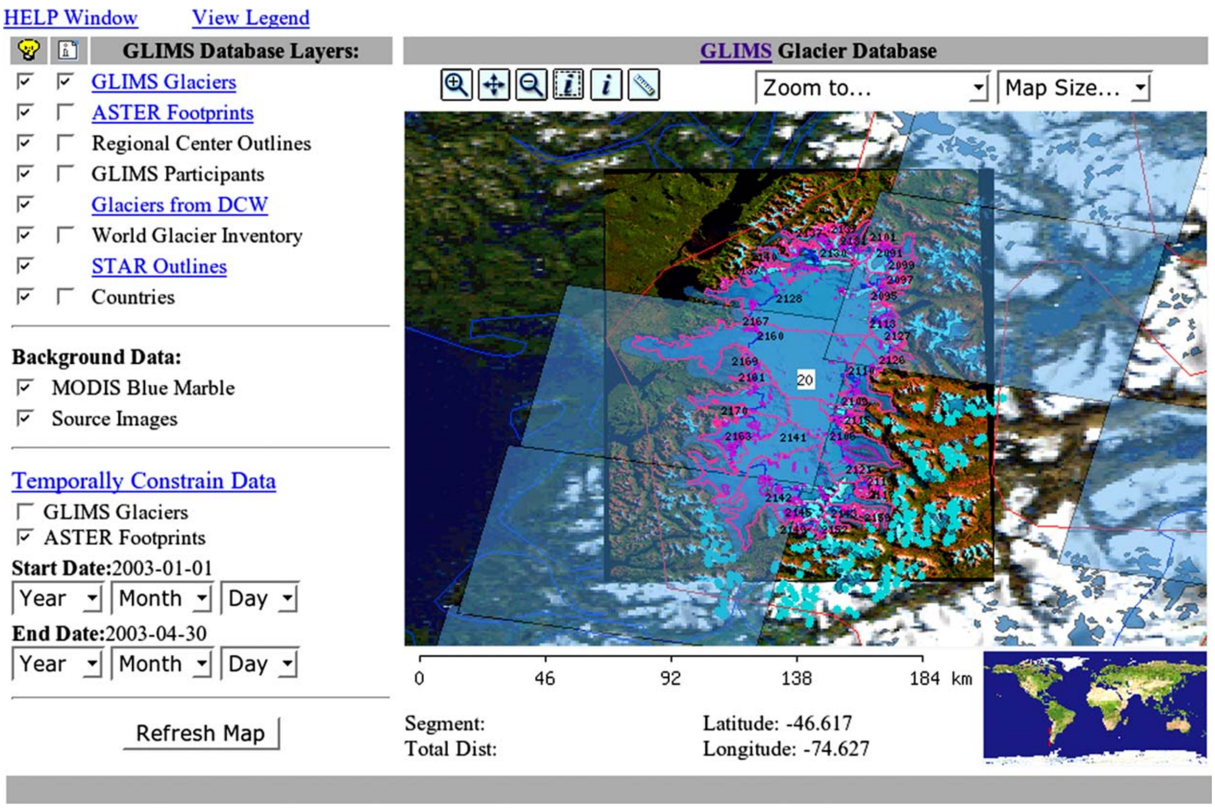

Fig. 2. Example of the MapServer interface in a browser. All layers are displayed, and are labeled in the column of check-boxes at left. GLIMS glaciers: detailed red outlines; ASTER footprints: translucent blue rectangles; Regional Center outlines: not visible at this scale; GLIMS participants; not visible in this view; glaciers from DCW: blue glacier outlines similar to GLIMS glaciers; World Glacier Inventory: light blue dots; STAR outlines: orange line circumscribing glacierized area; Countries: dark blue lines. The background image is the MODIS Blue Marble; the higher resolution image in center is the Landsat mosaic from which the GLIMS outlines were derived. Note that this example is a different location from that of the Example Application presented in this paper.

through either interface may be downloaded to the user's computer in a choice of GIS formats, including ESRI Shapefiles, Geography Markup Language (GML), MapInfo tables, and the multi-segment vector format used by the Generic Mapping Tools (GMT) software (Wessel and Smith, 1998). Turning the ASTER footprint layer on causes rectangular footprints representing ASTER images to be drawn on the map, and these can be queried to obtain information about the images such as image ID, acquisition date and time, and ASTER gain settings. For each footprint queried, a link to a browse image, also resident on our server, is provided.

The server can function as an Open Geospatial Consortium (OGC)-compliant Web Map Service (WMS), serving map layers to other Web map servers, or a Web Feature Service (WFS), which provides vector data to other data servers in GML, a machine-readable format. These functions allow other map servers to integrate the GLIMS glacier layers into their maps, facilitating easy use of GLIMS data by other disciplines and in ways not predictable by the GLIMS project. Similarly, the GLIMS map server can integrate layers from other OGC-compliant WMS and WFS servers, allowing us to display much more data on our maps than

Table 2
List of main layers in the GLIMS glacier database MapServer interface

Main layers in web map server	
Layer name	**Description**
GLIMS glacier	Glacier outlines, centerlines, snow lines, etc.
ASTER footprints	Footprints of ASTER images acquired over glaciers
Regional Center outlines	Areas of responsibility of RCs
GLIMS institution points	Locations of GLIMS institutions
Glaciers from DCW	Digital Chart of the World glacier layer
World glacier inventory	WGI data and metadata
STAR outlines	Glacierized areas that guide GLIMS ASTER acquisitions
Source images	Full resolution imagery analyzed for glacier outlines

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we host ourselves. We plan to improve the server to include outside layers (e.g. from other scientific disciplines that might have a connection to land ice) in the near future.

The interactive map capability, query interface, and OGC protocols are all implemented using the Open Source package MapServer. It connects directly to the PostGIS database, includes data from geolocated GeoTIFF images as well as ESRI Shapefiles, and presents interactive maps composed of these data sources. We have provided additional features (e.g. continuously updated display of latitude and longitude at cursor) using Javascript.

Regional Centers transfer GLIMS analysis results (outlines, etc. obtained from satellite imagery) via a web-based data submission interface. This password-protected interface allows GLIMS collaborators to keep their contact information up-to-date, facilitates the transfer of GLIMS data in a specially designed data format, and captures additional information from the analyst about processing steps used in the analysis. Processing details such as methods for image geolocation, radiometric calibration, topographic correction, and image classification and interpretation are captured in a web-form and are then stored in the database along with the glacier analysis results.

4. Example application – Cordillera Blanca, Peru

This section illustrates how multi-temporal data sources can be integrated in the GLIMS Glacier Database and used to investigate glacier changes. We produced one set of outlines from satellite imagery and ingested it into the GLIMS Glacier Database, along with glacier metadata and their attributes. In addition, the image analysis steps were stored in the database with the goal of facilitating multi-temporal analysis and

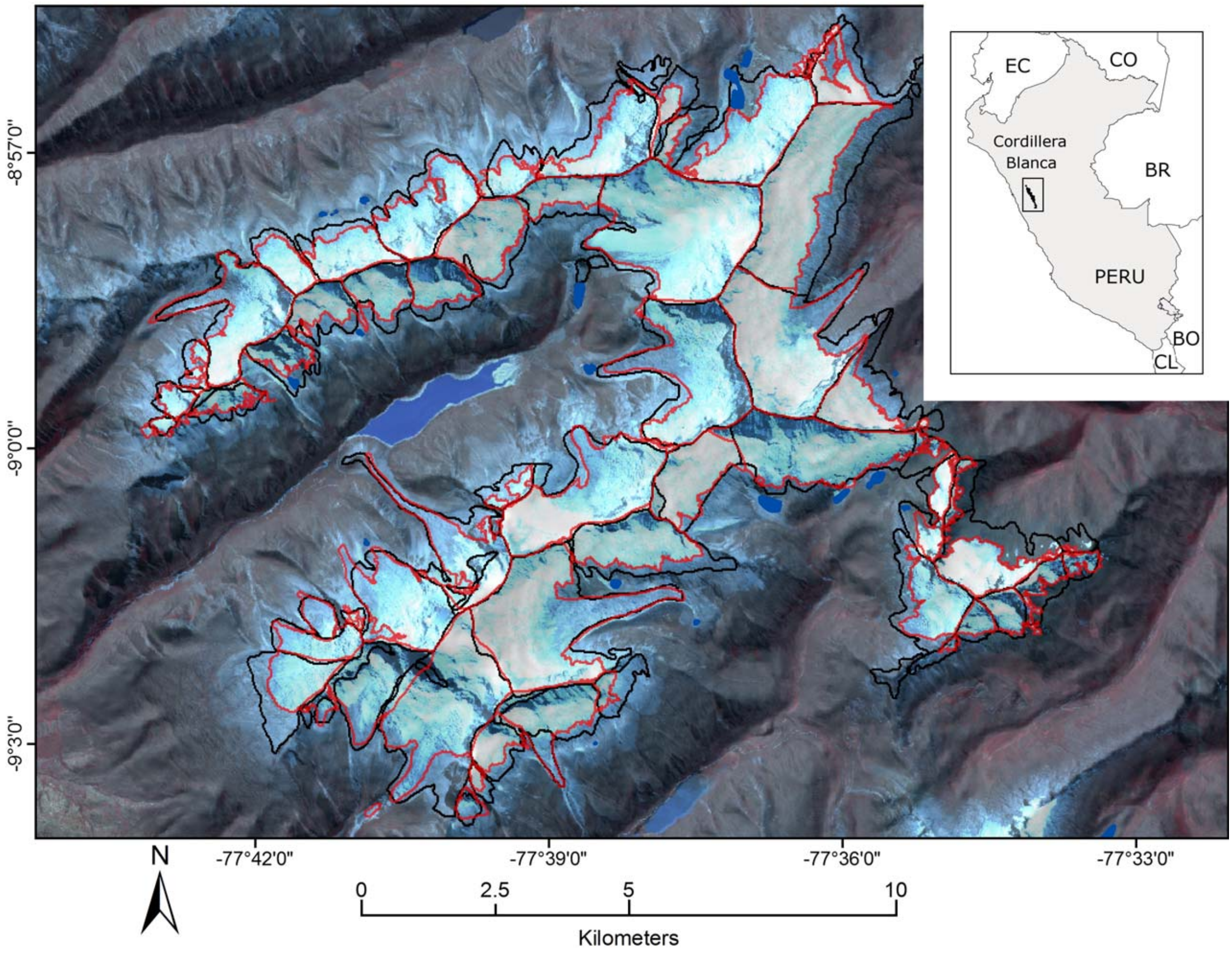

Fig. 3. The Huandoy–Artesonraju region of the Cordillera Blanca, Peru (ca. 9°S, 77.6°W), analyzed for this application example. Outlines from 1962R (Ames et al., 1989) are shown in black; 2003R glacier outlines of this paper are shown in red. The outlines are overlaid on a 2003 SPOT image, shaded to show topography.

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Table 3
Summary of measured glacier area changes from two previous studies and this one

Data source	Year (nickname)	Area (km^2)	Number of Glaciers
Ames et al., 1989			
	1962 (1962A)	103.6*	69
Georges, 2004			
	1962 (1962G)	81.9	
	1990	71	
	Area change 1970G–1990	−13%	N/A
This paper			
	1962 (1962R)	90.7	69
	2003 (2003R)	73	74
	Area change 1962R–2003R	−20%	
	Area change 1962A–2003R	−30%	
	Area change 1962G–2003R	−11	

The area marked with an asterisk was found to be imprecise by Georges, 2004, and was corrected in his study. Much of the difference between the Georges, 2003 area and that of this paper is attributable to varying definitions of what to include as "glacier". See text for further explanation.

estimating errors. Here we focus on existing problems encountered in comparing analyses done at different times and from different sources, and indicate how GLIMS aims to alleviate these problems.

The study area is situated in the Peruvian Cordillera Blanca (Fig. 3), that stretches for 180 km between 8.5° and 10° south latitude. It consists of 722 glaciers with an area of 723 km^2, according to an inventory based on 1962 and 1970 aerial photography (Ames et al., 1989). While much of this inventory is based on 1970 photographs, some of them are based on 1962 photographs. The particular glaciers focused on in this study were digitized from 1962 photographs.

For this study, we derived glacier outlines from two SPOT scenes with 10 m grid spacing from August 2003, covering the northern and southern parts of the Cordillera Blanca. Five mountain groups were outside the scenes and were not included in the study. In the data comparisons below, we discuss several inventories; for clarity, we have given them nicknames. The inventory containing our glacier outlines and associated metadata, based on the 2003 SPOT imagery, is dubbed "2003R". We compared this data set to glacier outlines from two other data sources: a paper-map glacier inventory based on 1962 aerial photography (Ames et al., 1989), to which we give the short name "1962A"; and a glacier inventory revised from 1962A and based on the same photography (Georges, 2004), which we call "1962G". We also obtained a digital version of the outlines in the 1962A data set, produced by the Instituto Geografico Nacional, and revised them (e.g. by adding some missing glaciers) to produce our own edited version, which we call "1962R". To derive elevation data for glaciers, we also used a digital elevation model (DEM) with 25 m grid spacing, created by interpolating contour lines from 1:100 000 topographic maps, which are based on 1962 aerial photography. We orthorectified the SPOT images using the DEM and 24 ground control points (GCPs) obtained with a differential GPS receiver. The horizontal and vertical uncertainty of the differentially corrected GCPs was less than 1 m, and the RMS error for the geocorrection was 5 m for both images, which is half of the pixel size.

We used a Normalized Difference Snow Index (NDSI) (Hall et al., 1995; Paul et al., 2002) with SPOT bands 1 and 4 (green and mid-infrared) and applied a threshold of −0.3 to extract initial glacier ice limits for each image. The glacier polygons were combined in a mosaic to create the raw ice polygons. We digitized debris-covered glaciers manually from a slope map and a color composite of SPOT bands 4, 3 and 2 displayed as red, green, blue, respectively. The ice coverage was visually checked for classification errors such as snow and rock outcrops, and classification of debris-covered termini was spot-checked using ground-based photographs where available. Ice divides were determined using watershed commands in ArcInfo, following algorithms developed by Manley (in press), and were used to separate the large contiguous ice masses into individual glaciers. The resulting polygons depicting glaciers and other glacial and periglacial features were coded using categories specified in the GLIMS Glacier Database, such as "internal rock", "glacier boundary", "proglacial lakes", "supraglacial lakes" and "debris boundary". Further steps included defining glacier centroids, matching glacier polygons

Table 4
Comparison of glacier elevations and areas for the Huandoy–Artesonraju massif region

Glacier ID	Min. Z (m) 1962	Min. Z (m) 2003	Change in min. Z (m)	Area 1962 (km^2)	Area 2003 (km^2)	Change in area (%)
PE1P005CFM01	4981	5049	68	0.84	0.65	−22.1
PE1P005CGF02	4895	4984	89	1.05	0.97	−7.84
PE1P005CGF03	4852	4975	123	1.16	0.92	−20.6
PE1P005CGH03	4275	4680	405	5.95	5.69	−4.40
PE1P005CIE02	4831	4886	55	2.37	1.87	−21.1
All 74 glaciers						
mean	4655	4711	56			
Sum				11.38	10.11	−11.2

Simple statistics for select glaciers included in this study are shown for years 1962 (revised from Ames et al., 1989) and 2003 (this study).

derived from SPOT imagery with point data from the World Glacier Inventory, determining parent IDs for glaciers that split into different parts, and assigning GLIMS glacier IDs based on location of the glacier (latitude and longitude coordinates).

The new glacier outlines were analyzed with the elevation data to derive several parameters for each glacier, including area, mean, minimum and maximum elevations, and average slope and aspect. Analysis steps were done with grid-based modeling and zonal functions based on approaches used by Paul et al. (2002) and Manley (in press). While the present analysis was done with digital elevation data from 1962, there may have been changes in surface elevation on glacier-covered areas (Vignon et al., 2003). At the time of this analysis, more recent elevation data were not available. We are currently constructing a new digital elevation model from ASTER scenes and SPOT stereo data for the extent of Cordillera Blanca and are re-quantifying changes in glacier parameters.

Our preliminary analysis results of the 2003 SPOT images are illustrated for a subset of the study area — the Huandoy–Artesonraju massif, which includes the benchmark glacier Arteson (Fig. 3). Outlines from both 1962R and 2003R are shown. For this mountain group, the image analysis yielded 74 main glaciers (compared with 69 in 1962R) with an area of 73 km^2. Table 3 provides a summary of measured glacier area changes from the present study (2003R) and two previous studies, 1962A and 1962G. The number of glaciers has increased due to a few glaciers breaking up into more than one piece as they shrink. Georges (2004) found the area estimate of 1970A (Ames et al., 1989) to be too high, and he corrected the number for his study. For the Huandoy–Artesonraju group only, these preliminary results indicate a reduction in glacier area of 20% in 41 years compared with 1962R, or 11% compared with 1962G (Georges, 2004). Table 4 summarizes elevation statistics for the 74 glacier termini in the subset of the study area, showing that glacier termini there have risen by approximately 60 m between 1962 and 2003. Fig. 4 shows histograms of elevation of the pixels within the Huandoy–Artesonraju group for both the 1962R and 2003R data sets. The histograms show a reduction in area and a loss of ice at lower elevations.

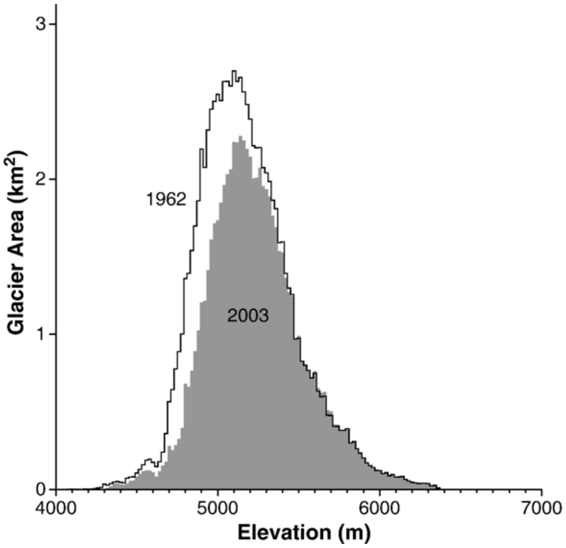

Fig. 4. Histogram of grid cell elevations for the glacierized regions of the Huandoy–Artesonraju group for data sets 1962R and 2003R. Histogram bin width is 20 m. The total area decrease of 20% is evident, as well as the overall shift to higher elevations of the glacier ice. The difference of the medians of the two distributions is 62 m.

5. Discussion

We found notable differences in both area estimates and number of glaciers between the results of this and previous studies. While remote-sensing methods have been used by our study and Georges (2004), as well as Silverio and Jaquet (2005), to update the 1962 glacial extents, there are differences in the estimates of glacial change. Much of the difference between the Georges, 2004 (1962G) area and that of this paper is attributable to varying definitions of what to include as “glacier”. The 1962G inventory excluded snow fields above the glacier accumulation zones, whereas we included them in 1962R. Differences in handling of rock outcrops contributed another (smaller) source of difference. Therefore, our calculated percent change in glacier area since 1962R may be underestimated.

While the 1962 data sets provide a basis for comparison with more recent remote-sensing inventories derived from satellite imagery (Landsat, ASTER and SPOT), there are systematic differences between data sets. First, the 1962A inventory of Cordillera Blanca was found to contain a number of discrepancies due to the methods used (digitizing with planimeters). For example, for the same study area, Georges (2004) revised the 1962 glacier extents and showed that ice areas were overestimated by Ames et al. (1989) by up to 10% because of included snow fields. Secondly, there are inconsistencies in the methodologies used to document and analyze glacier areas in previous inventories. Inactive ice (such as stagnant terminus lobes or peripheral snow fields) or rock outcrops may be counted differently, which creates inconsistencies in calculated total glacier areas. For example, Georges (2004) estimated the entire Cordillera Blanca glacier area to be 620 km^2 based on analysis of

1987 and 1991 SPOT scenes, indicating a retreat of 6% in the total glacier area from 1970 to 1990s. However, Silverio and Jaquet (2005) estimated the glacier area to be 643 km^2 in 1987, and 600 km^2 in 1996, based on analysis of Landsat images, indicating a retreat of more than 15% in 25 years, based on comparison with the Ames et al. inventory. The apparent increase in glacier area between 1990 (Georges, 2004) and 2003R is due to the inclusion of peripheral snowfields and stagnant debris-covered ice in the latter. Because of different methodologies used in the various studies, the estimates of glacial change in this area are inconsistent, ranging from −11% to −30% over the 1962–2003 time period.

We found the analysis of multi-temporal glacier change to be sensitive to the methods used to define and analyze ice areas. Future steps are needed to minimize large differences occurring in comparisons of glacier areas derived from various satellite data and those derived from old aerial photography or field survey. Inconsistencies such as the ones discussed here plague many glacier mapping studies, making global glacier change studies difficult. One way to address this is by comparing measurements of individual glaciers, and doing so only after making sure that the different measurements being compared were made using the same assumptions and definitions of what a "glacier" includes. We show comparisons of five selected glaciers in Table 4. We selected only a few for this example. These results show a large variability. In the case of these comparisons, done at the individual glacier level, the variability is due to differences in glacier response to regional climate changes. Aggregate comparisons between inventories can be made safely only if the inventories are confirmed to contain data on the same glaciers, with none missing from either inventory, and they must also treat glaciers using the same assumptions.

GLIMS aims to reduce or eliminate these consistency problems by establishing standard processing protocols (Raup et al., in press). Various researchers within the GLIMS community have been developing automatic glacier classification algorithms that will, once operational, consistently delineate glaciers from satellite imagery, facilitating direct meaningful comparisons between multi-temporal analyses of the same region (e.g. Bishop et al., 2004). Hurdles still remain on the path to full automation of glacier classification. For example, debris-covered glaciers require the use of topographic information for accurate delineation, and these techniques are still under development. But topographic and multispectral techniques for delineating the upper boundaries of glaciers are already showing promise (Manley, in press; Paul 2002). As GLIMS analysts follow protocols that use these algorithms, the resulting database will likely be much more consistent than past inventories that have been produced by researchers using various methods.

At the rate that many glacier systems are changing, comparisons between these various glacier inventories yield numbers that show significant glacier mass loss due to local or regional climate change, even when the inventories are not completely consistent (Khromova et al., 2003, for example). The increased consistency that the GLIMS consortium hopes to achieve will reduce the uncertainties in future measurements of glacier change.

6. Summary

The above example from the Cordillera Blanca illustrates the benefits of creating the GLIMS Glacier Database to facilitate studies of regional glacier change. GLIMS is striving to address the problem of inconsistent glacier inventories by establishing processing standards to ensure consistent data in the database. As the database grows to contain data from more and more regions of the world, it will enable analysis of glacier change at the global scale. Global patterns of glacier change, and how these patterns relate to global patterns of climate change, landmass distribution, terrain aspect, and other geomorphometric parameters will be ripe for investigation. Through use of the Open Geospatial Consortium protocols, servers of data from other scientific disciplines will be able to combine GLIMS glacier layers into their maps and data analysis systems. Interdisciplinary analysis may be used to investigate impacts of glacier changes on human activities, such as industry, natural resource exploitation, and recreation.

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