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Global Land Ice Measurements from Space (GLIMS): Remote Sensing and GIS Investigations of the Earth's Cryosphere

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Abstract

Concerns over greenhouse-gas forcing and global temperatures have initiated research into understanding climate forcing and associated Earth-system responses. A significant component is the Earth's cryosphere, as glacier-related, feedback mechanisms govern atmospheric, hydrospheric and lithospheric response. Predicting the human and natural dimensions of climate-induced environmental change requires global, regional and local information about ice-mass distribution, volumes, and fluctuations. The Global Land-Ice Measurements from Space (GLIMS) project is specifically designed to produce and augment baseline information to facilitate glacier-change studies. This requires addressing numerous issues, including the generation of topographic information, anisotropic-reflectance correction of satellite imagery, data fusion and spatial analysis, and GIS-based modeling. Field and satellite investigations indicate that many small glaciers and glaciers in temperate regions are downwasting and retreating, although detailed mapping and assessment are still required to ascertain regional and global patterns of ice-mass variations. Such remote sensing/GIS studies, coupled with field investigations, are vital for producing baseline information on glacier changes, and improving our understanding of the complex linkages between atmospheric, lithospheric, and glaciological processes.

Introduction

The purpose of this article is to demonstrate the role of remote sensing and GIS in an international science project designed to assess the worlds' glaciers from space; the Global Land-ice Measurements from Space (GLIMS) project. By necessity, only a sample of some key geographic areas can be presented, as well as a few other regions where more plentiful glacier information is available. Specifically, we address the significance of understanding ice-mass

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fluctuations, describe the role of remote sensing and GIS investigations in glaciological research, address unique challenges for accurate information extraction from satellite imagery, and provide preliminary results based upon field investigations and remote sensing/GIS studies.

Concerns over greenhouse-gas forcing and warmer temperatures have initiated research into understanding climate forcing and associated Earth-system responses. Considerable scientific debate occurs regarding climate forcing and landscape response, as complex geodynamics regulate feedback mechanisms that couple climatic, tectonic and surface processes (Molnar and England, 1990; Ruddiman, 1997; Bush, 2000; Zeitler *et al*., 2001; Bishop *et al*., 2002). A significant component in the coupling of Earth's systems involves the cryosphere, as glacier-related feedback mechanisms govern atmospheric, hydrospheric and lithospheric response (Bush, 2000; Shroder and Bishop, 2000; Meier and Wahr, 2002). Specifically, glaciers partially regulate atmospheric properties (Henderson-Sellers and Pitman, 1992; Kaser, 2001), sea level variations (Meier, 1984; Haeberli *et al*., 1998; Lambeck and Chappell, 2001; Meier and Wahr, 2002), surface and regional hydrology (Schaper *et al*., 1999; Mattson, 2000), erosion (Hallet *et al*., 1996; Harbor and Warburton, 1992, 1993), and topographic evolution (Molnar and England, 1990; Brozovik *et al*., 1997; Bishop *et al*., 2002). Consequently, scientists have recognized the significance of understanding glacier fluctuations and their use as direct and indirect indicators of climate change (Kotlyakov *et al*., 1991; Seltzer, 1993; Haeberli and Beniston, 1998; Maisch, 2000). In addition, the international scientific community now recognizes the need to assess glacier fluctuations at a global scale, in order to elucidate the complex, scale-dependent interactions involving climate forcing and glacier response (Haeberli *et al*., 1998; Meier and Dyurgerov, 2002). Furthermore, it is essential that we identify and characterize those regions that are changing most rapidly and having a significant impact on sea level, water resources, and natural hazards (Haeberli, 1998).

High-latitude and mountain environments are known for their complexity and sensitivity to climate change (Beniston, 1994; Mysak *et al*., 1996; Meier and Dyurgerov, 2002). In addition to the continental ice masses, several geographic regions have been identified as "critical regions" and include Alaska, Patagonia and the Himalaya (Haeberli, 1998; Meier and Dyurgerov, 2002). Although smaller in extent, alpine glaciers are thought to be very sensitive to climate forcing due to the altitude range and/or the variability in debris cover (Nakawo *et al*., 1997). Furthermore, such high-altitude geodynamic systems are considered to be the direct result of climate forcing (Molnar and England, 1990; Bishop *et al*., 2002), although climatic versus tectonic causation is still being debated (e.g., Raymo *et al*., 1988; Raymo and Ruddiman, 1992). Central to various geological and glaciological arguments is obtaining a fundamental understanding of the feedbacks between climate forcing and glacier response (Hallet *et al*., 1996; Dyurgerov and Meier, 2000). This requires detailed information about glacier distribution and ice volumes, annual mass-balance, regional mass-balance trend, and landscape factors that control ablation. From a practical point-of-view, the extremely rapidly changing glaciological, geomorphological and hydrological conditions in the cryosphere, present to many regions of the world, a "looming crisis", in terms of a decreasing water supply, increased hazard potential, and in some instances, geopolitical destabilization.

Scientific progress in understanding these remote environments, however, has been slow due to logistics, complex topography, paucity of field measurements, and limitations associated with information extraction from satellite imagery. Problems include the paucity and/or quality of information on: (1) enumeration and distribution of glaciers; (2) glacier mass-balance gradients and regional trends; (3) estimates of the contribution of glacial meltwater to the observed rise in sea level; and (4) natural hazards and the imminent threat of landsliding, ice and moraine dams, and outburst flooding caused by rapid glacier fluctuations.

McClung and Armstrong (1993) have indicated that detailed studies of a few well-monitored glaciers do not permit characterization of regional mass-balance trends, the advance/retreat behavior of glaciers, or global extrapolation. Given our current rate of collecting glacier information, it is expected that far too many glaciers will be entirely gone before we can measure and understand them. This time-sensitive issue requires us to continue to acquire global and regional coverage of glaciers via satellite imagery before they disappear. As time is of the essence, a certain level of automation is required, although numerous challenges remain regarding information extraction and validation. Consequently, an integrated approach to studying the cryosphere must be accomplished using remote sensing and GIS investigations to improve our understanding of climate forcing and glacier fluctuations (Haeberli *et al*., 1998, 2004).

Background

Climate Forcing

The spatio-temporal dynamics that govern the coupled atmosphere-ocean-cryosphere system are only beginning to be exposed through a series of observational, theoretical, and numerical studies. With the increasing availability of global satellite data, however, a barrage of statistical analyses (e.g., empirical orthogonal functions, cross-correlation analysis, singular-value decomposition) has identified the climatic signatures of a number of oscillations to which this coupled system is subject. These oscillations act across a very broad range of timescales, from seasonal to decadal and, invoking results from numerical climate models, also extend into the centennial to millenial range. Observed climatic oscillations have very well-defined spatial signatures in meteorological variables such as surface temperature, pressure, or precipitation. They therefore affect, quite fundamentally, cryospheric processes at the Earth's surface.

The best example of annual variability is, of course, the seasonal cycle of incoming solar radiation. It determines the latitudinal distribution of temperature and the mean location at which the westerly jet streams occur during any given month (Barry and Carleton, 2001). Internal variability within the climate system, however, causes the seasonal cycle to be slightly different from year to year. The resulting latitudinal vacillations of the westerly jets are believed to be ultimately responsible for the North and South Annular Modes (e.g., Thompson and Wallace, 2000), the former of which has been linked to the North Atlantic/Arctic Oscillation (e.g., Limpasuvan and Hartmann, 2000) and hence influences Arctic sea ice (e.g., Venegas and Mysak, 2000).

The best example of interannual variability is the El Niño Southern Oscillation (ENSO), a coupled atmosphere-ocean phenomenon whose internal workings are relatively well understood and predictable within approximately 6-8 months. ENSO appears to be fundamentally correlated to the south Asian monsoon and hence to snow and ice accumulation in the Himalaya (Bush, 2002). In addition, correlation of ENSO with sea ice concentration in the Arctic (e.g., Mysak *et al*., 1996) demonstrates that even tropical climate variability influences high-latitude cryospheric processes.

On longer timescales, the Pacific Decadal Oscillation and centennial climate variability also appear to have significant global signatures in temperature and precipitation, and will also play a role in crysopheric dynamics at the Earth's surface.

The global nature of many of these oscillations demands that any observational network that attempts to explain them be global, or at least hemispheric, in extent. Therefore, satellite remote sensing is an integral component to research on climate variability. In addition, those geographic regions that are particularly susceptible to such variability should have additional monitoring. Those locations that comprise Earth's cryosphere are prime examples of such sensitive regions. The high-latitudes and high-mountain regions have been flagged as the "canary in the coal mine" of climate change because of the cryosphere's rapid response to climate perturbations. In addition, interannual and decadal variability is exhibited in the low-latitude high-altitude cryosphere of the Himalaya and the Andes.

The responses of ocean and atmospheric circulation patterns to changes in the cryosphere, and the feedbacks prevailing in such interactions, are new and emerging themes of climate research. Historically considered dynamic on only very slow timescales, the Earth's cryosphere is rapidly proving itself to be a major player in climate oscillations on every timescale.

Water Resources

The global hydrologic cycle of the Earth is absolutely critical for sustaining the biosphere, and its components are quantitatively measured and accounted for in hydrologic, or mass-balance, water-flow budgets. Rational water management should be founded upon a thorough understanding of water availability and movement (Haeberli *et al*., 1998), which requires monitoring of all the essential elements. The most significant elements of the hydrologic cycle are: (1) the volumes of solid, liquid, and gas within the subsystems; (2) residence times during which a unit remains within a subsystem reservoir; and (3) paths of motion from one system to another. Fresh water in the form of ice constitutes about 80 percent of the water that is not in oceans, which is far greater than any other stored source, and also about 2 percent of the total water on the planet. Most ice in the cryosphere occurs in the ice sheets covering Greenland and Antarctica, where it may reside for thousands to millions of years before returning as icebergs and meltwater to the sea, or as vapor to the atmosphere.

On the other hand, the snow- and ice-covered mountains of the world constitute the water towers of vital supply for hundreds of millions of the world's people. In some places, however, such as Afghanistan, glacier-ice resources have been dramatically reduced in the past few decades of drought and increased melt, and downstream water discharges have been reduced catastrophically (Shroder, 2004a). In many places though, each annual melt of snow and ice resources recharges the river basins and reservoirs of the world. But world-water use per person has also doubled in the past century, and is expected to become an increasingly scarce and ever-more contentious commodity in coming years (Gleick, 2001; Aldous, 2003). Furthermore, climate change could bring hydrological chaos, even with an average temperature rise of only a few degrees C over the coming century, which is expected to bring more rain, less snow, and more and earlier melting. This may halve snowpack volumes and increase flood and landslide hazards, especially in winter and spring seasons (Gleick, 2003). It is thus essential to establish a better means to measure, model, and plan for future climates.

Asrar and Dozier (1994) have noted that understanding of how global change may influence world-wide water balances will require information about spatial and temporal variations in storage of water in its various reservoirs, and magnitude of transfers between reservoirs. Most important will be working out the best methods to determine interannual variability of global hydrologic processes, from natural variability and the seasonal cycle, to infer mechanisms and magnitudes of climate change. Newly developed continental- and regional-scale surface hydrologic models include explicit treatment of precipitation, runoff, soil moisture, and snow and ice dynamics over the land (Asrar and Dozier, 1994).

Kump (2002) has pointed out, however, that the lack of an adequate ancient analogue for future climates means that we ultimately must use and trust climate models evaluated against modern observations of existing climates and water storages and discharges, using the best geologic records of warm and cold climates of the past. Armed with an elevated confidence in the models, more reliable predictions can then be made of the Earth's response to risky human inputs into the climate system. In addition, the hydrologic cycle in deep-time climate problems is presently the target of intensive research (Pierrehumbert, 2002) to better understand whatever difficult world-water situation we are going to face in the future. This includes the expected highly problematic, sea-level rise as the cryosphere continues to melt (Lambeck *et al*., 2002).

In fact, ice-mass changes in the cryosphere are among the safest or most reliable natural evidence of ongoing changes in the energy balance at the Earth's surface and, hence, can be considered as essential information for early detection of climate warming from human or natural causes in the near future (Haeberli, 1998). The many problems of logistics, funding, maintenance of long-term monitoring, lack of truly representative field coverage, as well as quite limited coverage of any kind in many third world areas, means that remote sensing and GIS investigations, coupled with field control where possible, are vital to maintaining adequate information on the water-storage resources of snow and ice in the headwater basins of many of the world's great watersheds.

Natural Hazards

Extreme natural events occur in seasonal, annual, or secular fluctuations of processes that constitute hazard to humans, to the extent that their adjustments to the frequency, magnitude, or timing of the natural extremes are based upon imperfect knowledge (White, 1974). Many natural hazards are subject to assessment and prediction through the use of remote sensing and GIS technology. The GLIMS project is ideally suited to provide essential information for certain natural hazards that are of increasing concern to people in many parts of the world (Huggel *et al*., 2002).

Hazards in the cryosphere represent a continuous and growing threat to human lives and infrastructure, especially in high-mountain regions. In the future, however, the threat may also be from rapid surge or massive calving of polar ice caps and catastrophic rise of sea level world-wide, which would drown port cities and even eliminate some island nations entirely. At the present time, cryosphere-related disasters (e.g., glacial-lake outburst floods, glacial surges, debris flows, landslides, avalanches) in mountains can kill hundreds or even thousands of people at once and cause damage with costs on the order of $ 100 million annually. Present-day trends in climatic warming especially affect terrestrial systems where surface and subsurface ice are involved. Changes in glacier and permafrost equilibria are shifting hazard zones beyond historical experience or knowledge, which makes prediction more difficult. Furthermore, as world populations increase, human settlements and activities are being extended towards endangered zones. As a consequence, empirical knowledge will have to be increasingly replaced by improved understanding of process.

The recently accelerated retreat of glaciers in nearly all mountain ranges of the world has led to the development of numerous potentially dangerous lakes (Mool *et al*., 2001a,b), which can break out in devastating floods (Coxon *et al*., 1996; Shroder *et al*., 1998; Cenderelli and Wohl, 2001). In 2002, the United Nations Environment Program (UNEP), therefore, launched a high-level warning system in view of the dramatic growth of gigantic glacier lakes in the Himalaya. At the present time, the main hazards from the cryosphere recognized in mountain regions are: (1) the outburst of glacier lakes, causing floods and debris flows; (2) avalanche/landslide-induced wave impacts on glacial-lake dams; (3) ice break-offs and subsequent ice avalanches from steep glaciers; (4) stable and unstable (surge-type) glacier length variations; (5) destabilization of frozen or unfrozen debris slopes; (6) destabilization of rock walls, as related to glacial and periglacial activity; (7) adverse effects of rock glaciers; and (8) combinations or complex chain reactions of these processes.

In addition, increasing recognition of these hazards has led to a new proposal for the establishment of an inter-divisional Working Group of the International Commission on Snow and Ice (ICSI) within the International Association of Hydrological Sciences (IAHS) of the International Union of Geodesy and Geophysics to address glacier and permafrost hazards in high mountains. The Working Group plans to address issues dealing with: (1) processes involved in formation of glacier and permafrost hazards; (2) techniques and strategies for mapping, monitoring, and modeling; (3) methods of hazard vulnerability and risk assessment; (4) methods of hazard mitigation, including styles and effectiveness of remedial works; and (5) raising awareness of protocols for hazard assessment and remediation. In this fashion, the ICSI Working Group aims to improve international scientific communications on cryospheric hazards to government agencies, and the media, as well as to provide up-to-date advice and information to other relevant groups. GLIMS will contribute to the process with new satellite-based observations.

Glacier Observations

Fluctuations of glaciers and ice caps have been systematically observed for more than a century in various parts of the world (Williams and Ferrigno, 1989; Haeberli *et al*., 1998; Williams and Ferrigno, 2002b) and are considered to be highly reliable indications of worldwide warming trends (e.g., Fig. 2.39a in IPPC, 2001). Mountain glaciers and ice caps are, therefore, key variables for early-detection strategies in global climate-related observations. Within the framework of the global, climate-related, terrestrial-observing systems, a Global Hierarchical Observing Strategy (GHOST) was developed to be used for all terrestrial variables. According to a corresponding system of tiers, the regional to global representativeness in space and time of the records relating to glacier mass and area should be assessed by more numerous observations of glacier-length and thickness changes, as well as by compilations of regional glacier inventories repeated at time intervals of a few decades - the typical dynamic response time of mountain glaciers (Haeberli *et al*., 2000). The individual tier levels are as follows:

- Tier 1 (multi-component system observation across environmental gradients).

  Primary emphasis is on spatial diversity at large (continental-type) scales or in elevation belts of high-mountain areas. Special attention should be given to long-term measurements. Some of the already observed glaciers (for instance, those in the American Cordilleras or in a profile from the Pyrenees through the Alps and

Scandinavia to Svalbard) could later form part of Tier 1 observations along large-scale transects.

- Tier 2 (extensive glacier mass balance and flow studies within major climatic zones for improved process understanding and calibration of numerical models).
  Full parameterization of coupled numerical energy/mass balance and flow models is based on detailed observations for improved process understanding, sensitivity experiments and extrapolation to areas with less comprehensive measurements. Ideally, sites should be located near the center of the range of environmental conditions of the zone that they are representing. The actual locations will depend more on existing infrastructure and logistical feasibility rather than on strict spatial guidelines. Site locations should represent a broad range of climatic zones (such as tropical, subtropical, monsoon-type, midlatitude maritime/continental, subpolar, polar).
- Tier 3 (determination of regional glacier volume change within major mountain systems using cost-saving methodologies).
  Numerous sites exist that reflect regional patterns of ice-mass change within major mountain systems, but they are not optimally distributed (Cogley and Adams, 1998). Observations with a limited number of strategically selected index stakes (annual time resolution) combined with precision mapping at about decadal intervals (volume change of entire glaciers) for smaller ice bodies or with laser altimetry/kinematic GPS (Arendt *et al*., 2002) for large glaciers constitute optimal possibilities for extending the information into remote areas of difficult access. Repeated mapping and altimetry alone provide important data at lower time resolution (decades).
- Tier 4 (long-term observation data of glacier-length change within major mountain ranges for assessing the representativity of mass balance and volume change measurements).
  At this level, spatial representativeness is the highest priority. Locations should be based on statistical considerations (Meier and Bahr, 1996) concerning climate characteristics, size effects and dynamics (calving, surge, debris cover etc.). Long-term observations of glacier-length change at a minimum of about 10 sites within each of the mountain ranges should be measured either in-situ or with remote sensing at annual, to multi-annual frequencies.
- Tier 5 (glacier inventories repeated at time intervals of a few decades by using satellite remote sensing).
  Continuous upgrading of preliminary inventories and repetition of detailed inventories using aerial photography or, in most cases satellite imagery, should enable global coverage and permit validation of climate models (Beniston *et al*., 1997). The use of digital terrain information and GIS technology greatly facilitates automated procedures of image analysis, data processing and modeling/interpretation of newly available information (Haeberli and Hoelzle, 1995; Bishop *et al*., 1998a, 2000; Kääb *et al*., 2002; Paul *et al*., 2002). Preparation of data products from satellite measurements must be based on a long-term program of data acquisition, archiving, product generation, and quality control.

This integrated and multi-level strategy aims at integrating in-situ observations with remotely sensed data, process understanding with global coverage, and traditional measurements with new technologies. Tiers 2 and 4 mainly represent traditional methodologies that remain fundamentally important for deeper understanding of the involved processes, as training components in environment-related educational programs and as unique demonstration projects for the public. Tiers 3 and 5 constitute new opportunities for the application of remote sensing and GIS.

A network of 60 glaciers representing Tiers 2 and 3 was established. This step closely corresponds to the data compilation published so far by the World Glacier Monitoring Service with the biennial Glacier Mass Balance Bulletin and also guarantees annual reporting in electronic form. Such a sample of reference glaciers provides information on presently-observed rates of change in glacier mass, corresponding acceleration trends and regional distribution patterns. Long-term changes in glacier length must be used to assess the representativity of the small sample of values measured during a few decades with the evolution at a global scale and during previous time periods. This can be done by: (1) intercomparison between curves of cumulative, glacier-length change from geometrically similar glaciers; (2) application of continuity considerations for assumed step changes between steady-state conditions reached after the dynamic response time (Hoelzle *et al*., 2003); and (3) dynamic fitting of time-dependent flow models to present-day geometries and observed long-term length change (Oerlemans *et al*., 1998). New detailed glacier inventories are now being compiled in areas not covered so far in detail or, for comparison, as a repetition of earlier inventories. This task has been greatly facilitated by the implementation of the international GLIMS project (Kieffer *et al*., 2000). Remotely sensed data at various scales (satellite imagery, aerophotogrammetry) and GIS technologies must be combined with topographic information (Hall *et al*., 1992, 2000; Bishop *et al*., 2000, 2001; Kääb *et al*., 2002; Paul *et al*., 2002) in order to overcome the difficulties of earlier satellite-derived preliminary inventories (area determination only) and to reduce the cost and time of compilation. In this way, it should be feasible to reach the goals of global observing systems in the years to come.

International GLIMS Project

The international GLIMS project is a global consortium of universities and research institutes, coordinated by the United States Geological Survey (USGS) in Flagstaff, Arizona, whose purpose is to assess and monitor the Earth's glaciers. Glaciers play a significant role in Earth system dynamics, and control the natural resource potential for many regions of the world. Specifically, GLIMS objectives are to ascertain the extent and condition of the world's glaciers so that we may understand a variety of Earth surface processes and produce information for resource management and planning. These scientific, management and planning objectives are supported by the monitoring and information production objectives of the United States government and United Nations scientific organizations, and are central to the ongoing economic and geopolitical discussions about resource availability and geopolitical stability.

GLIMS entails: (1) comprehensive satellite multispectral and stereo-image acquisition of land ice on an annual basis; (2) use of satellite imaging data to measure inter-annual changes in glacier length, area, boundaries, and snowline elevation; (3) measurement of glacier ice-velocity fields; (4) assessment of water resource potential; (5) development of a comprehensive digital database to inventory the world's glaciers, with pointers to other data and relevant scientific publications; and (5) rigorous validation of the GLIMS glacier database. This work and the global image archive will be useful for a variety of scientific and planning applications.

GLIMS's objectives are being achieved through: (1) involvement in observation planning of satellite data; (2) use of a liberal data distribution policy to disseminate satellite images to GLIMS collaborators; (3) development of an international consortium of research institutes (Regional Centers), where image analysis and modeling for glacier status and changes can be conducted; (4) reliance on other glaciological and remote sensing institutes, such as the National Snow and Ice Data Center (Boulder, CO) and the EROS Data Center (Sioux Falls, SD) to provide critical services lacking elsewhere in the GLIMS structure; and (5) creation of a robust and publicly accessible database for storage and manipulation of the glaciological data to be derived by consortium members. The GLIMS web-site (http://www.glims.org) provides additional information about the project.

GLIMS will primarily utilize multispectral imaging for assessment of glacier state and dynamics (e.g. ASTER data). Various approaches and techniques have produced impressive, ground-validated results, while other approaches remain to be rigorously validated, while others are still in an exploratory phase of development. We can identify, however, some critical limitations of multispectral imaging even with foreseen advances in sensors, data and methods. Consequently, GLIMS will increasingly utilize the integration of solar reflective, thermal and microwave remote sensing to assist in glacier analysis to address the limitations of multispectral approaches which include: 1) difficulty in differentiating subpixel mixtures of ice, water and rock; 2) multi-scale topographic effects on sensor response; 3) difficulty in assessing small-magnitude glacier surface displacements given spatial resolution and short-term temporal coverage; 4) image coregistration issues given higher spatial resolution sensors; 5) DEM errors due to reflectance saturation and technical issues related to particular methods of computing parallax and transforming parallax into surface relief; 6) atmospheric effects; 7) daylight imaging; and 8) lack of internal information regarding ice depth, flow and deformation (i.e. supraglacial versus englacial and basal information).

Thermal, microwave, and light detecting and ranging (LIDAR) sensors can compensate for some, though not all, of these limitations. These systems have their own limitations, but an integrated approach to glacier analysis is more robust. This is a key future direction of the GLIMS project.

Synthetic aperture radar (SAR) imaging and Interferometric SAR (InSAR) analysis have produced revolutionary advances in remote sensing of glaciers. SAR and InSAR can compensate for a number of the aforementioned limitations. SAR systems have all-weather and day/night acquisition capabilities. The dielectric properties of snow, ice, and rock are such that SAR enables differentiation of those materials in glacier areas, permitting mapping of the recession of snow, rock abundance, surface wetting, and shallow ice structure. Multi-band SAR has proven itself for accurate mapping of rock-size distributions, and facilitates the mapping of snow, ice and firn facies. Consequently, it can be used to map the transient melting-altitude line. Ice-penetrating radar is also able to map internal features, such as horizons of volcanic ash and other ice layers and basal topography.

InSAR can provide short-term glacier displacements and interannual changes in glacier surface height continuously over an entire glacier. In a remarkable complementary fashion, InSAR can assess short-term ice-velocity vector fields of glaciers (over periods of days to months, depending on flow speeds) but not long-term changes, while multispectral approaches can assess long-term ice-velocity vector fields and other glacier fluctuations (over months to years, depending on flow speeds).

EROS Data Center

The USGS EROS Data Center (EDC) is the host institution for the Land Processes Distributed Active Archive Center (LP DAAC) that is funded by NASA to support its Earth Observing System (EOS) Mission. The LP DAAC is responsible for the archive and distribution of MODIS land data products, and it is the primary archive, processing, and distribution facility for ASTER data. In addition, the LP DAAC archives Level-0R data acquired by the Landsat 7 enhanced thematic mapper plus (ETM+) instrument and is co-located at the EDC with the Landsat 7 ground station and processing systems. Given the mission responsibilities and the systems capabilities in place, the EDC has been in a position to assist the GLIMS project in data acquisition scheduling, data processing, and data access and distribution.

The LP DAAC receives ASTER data from the ground data system (GDS) in Japan, where the data are processed to Level-1A (radiometric and geometric calibration coefficients appended) and Level-1B (radiometric and geometric calibration coefficients have been applied). Depending on cloud cover and scene quality, a variable number of the Level-1A data are routinely processed to Level-1B. The algorithms used to quantify cloud cover extent are particularly challenged over glacier environments because of the need to discriminate between snow, ice, and various types of cloud cover. In fact, clouds are a critical factor by which the ASTER GDS determines which scenes to process to Level-1B. Consequently, the amount of Level-1B data available over many glaciers remains low. Accurate radiometric calibration, co-registration of the 14 spectral bands, and geographic referencing of the data are required in order to perform quantitative image analysis and generate higher-level data products.

In order to monitor the status of data acquisition requests (DARs) submitted by the GLIMS project relative to the scenes that were actually acquired, as well as the level to which they had been processed by the ASTER GDS, the LP DAAC provided regular metadata exports from the ASTER inventory database to the GLIMS Coordination Center in Flagstaff. This included attributes such as scene-id, acquisition date and time, scene coordinates, percent cloud cover, DAR-id, and gain settings. These metadata were incorporated into a project database that enabled graphic display of the geographic coverage of ASTER data and the ability to query metadata attributes (http://www.glims.org/astermap.html).

For glaciers where ASTER Level-1B data were unavailable, Landsat 5 thematic mapper (TM) and Landsat 7 ETM+ scenes were acquired to fill gaps in the ASTER coverage. More than 100 Landsat 7 ETM+ and Landsat 5 thematic mapper (TM) scenes were purchased and made available to GLIMS investigators. The LP DAAC established a suite of online data directories allowing ftp access to ETM+ and ASTER scenes acquired for the project. These data directories are organized by Regional Center (http://www.glims.org/icecheck.html) and contain subdirectories for each instrument. The subdirectories for the ETM+ and TM data are organized by path/row of the World Reference System 2 (WRS-2).

Recently, the LP DAAC completed local testing of the ASTER GDS Level-1B processing algorithms and system performance in the event that selective Level-1B processing would be required in the future. NASA and the ASTER GDS agreed to allow the LP DAAC to process 2800 scenes for GLIMS as part of the performance testing. We are currently in the process of manually assessing the cloud cover and scene quality of these Level-1B data. A spreadsheet containing ASTER scene information (database-ID, filename, acquisition date & time, scene center latitude & longitude) and the results from manual assessment (cloud-cover percent, scene quality comments) are maintained, and reduced resolution JPEG images are also being created. As the individual ASTER Level-1B scenes are examined, cloud-cover extent is estimated and entered into the spreadsheet along with other relevant comments on data quality anomalies, and the JPEG images are created. Groups of 40 JPEG images are archived and compressed into a Winzip file and are stored along with the most current version of the spreadsheet on the FTP server. The ASTER Level-1B data files are placed under the appropriate GLIMS Regional Center ASTER subdirectory for access by GLIMS investigators.

Unique events/emergencies may require immediate data acquisitions, such as the Kolka Glacier collapse (Kääb *et al*., 2003), and ASTER data acquisition requests can be scheduled. Once the data have been acquired by the instrument and down-linked to NASA Goddard Space Flight Center, they are delivered electronically to the LP DAAC for expedited processing and staged for FTP access. ASTER expedited data are typically available within 6 hours of acquisition by the instrument. In other cases, such as monitoring fracture development on the Amery Ice Shelf, out-of-cycle Landsat 7 ETM+ acquisitions have been scheduled. If necessary, the ETM+ acquisitions can be written to the solid state recorder onboard the spacecraft for direct down-link to the ground station at EDC, enabling the data to be processed and made available in less than 24 hours after acquisition.

National Snow & Ice Data Center

Complete regional databases and incomplete global databases of Earth's glaciers exist, however, there are currently no geographically complete, global-glacier databases. A major task of GLIMS is to produce a comprehensive global database so that scientists can investigate local, regional and global changes and interrelationships.

The results of glacier analysis done by GLIMS Regional Centers, including thematic/spatial information (e.g., land cover, glacier outlines, snowlines, centerlines) and basic scalar attributes (e.g., glacier length, width, and flow speed), are sent to the National Snow and Ice Data Center (NSIDC) for archiving in the GLIMS Glacier Database. NSIDC has implemented a relational database designed to permit information storage regarding glaciers, base imagery, relevant literature references, and supporting spatial data such as DEMs (see http://www.glims.org/ for a complete description). The database is also designed to store information about the complex relationships between different glaciers. For example, as glaciers melt, glaciers that formerly were connected as one ice mass may separate and become distinct ice masses. The database permits storage of such 'parent-child' relationships.

Database information can be searched and retrieved over the World Wide Web. Database queries can be constrained geographically, temporally, or by establishing glacier-attribute magnitude limits. For example, a typical query might be, "itemize all the glaciers in the southern hemisphere that move faster than 50 meters per year, and which calve icebergs". In the near future, NSIDC plans to augment this interface to enable graphical map-based searches as well. This work will include the implementation of a Web-Map Server and Web-Coverage Server, both interfaces specified by the OpenGIS Consortium (http://www.opengis.org).

The GLIMS Glacier Database will allow detailed analysis of global trends and patterns of change that transcend regional scope (e.g., Dyurgerov and Meier, 1997; Dyurgerov and Bahr, 1999; McCabe *et al*., 2000; Dyurgerov and Meier, 2000; Meier and Dyurgerov, 2002). The importance of this global-glacier database lies in its ability to answer queries across all regions, enabling researchers to identify global patterns related to the cryosphere/climate systems.

Digital Terrain Data

Within GLIMS, orthorectification of satellite imagery, retrieval of three-dimensional glacier parameters and other procedures and corrections require the use of topographic information (i.e., DEMs) covering large glacierized areas. For DEM-generation, GLIMS presently focuses on stereoscopic satellite imagery, but will upon availability, increasingly consider data from the Shuttle Radar Topographic Mission (SRTM) and other spaceborne, synthetic-aperture, radar interferometry, missions.

Stereo satellite imagery is either recorded from repeated imaging of the terrain with different view angles, i.e., from different satellite tracks (*cross-track stereo*), or during one overflight by nadir, forward and/or backward looking *along-track stereo* channels. Multi-temporal SPOT data from different pointing-angles have been widely used for DEM generation over mountainous terrain (e.g., Al-Rousan and Petrie, 1998; Bishop *et al*., 2000; Zomer *et al*., 2002).

If available, along-track stereo is preferable for most applications in glaciology, since the data are obtained within one overflight, during which terrain changes are minor. Over the much longer time spans between the stereo partners of cross-track stereo imagery (up to months and years), the terrain conditions might change significantly and complicate image correlation, for instance, by snow-fall or melt. Within GLIMS, DEMs are primarily computed from ASTER along-track stereo (Figure 1) (Kääb, 2002; Kääb *et al*., 2002; Hirano *et al*., 2003).

For generating DEMs from ASTER data, either corrected level 1B data are applied, or level 1A data, which are destriped using the respective parameters provided by the image header information. Orientation of the 3N and accordant 3B band (Figure 1) from ground control points (GCP), transformation to epipolar geometry, parallax-matching, and parallax-to-DEM conversion is, for instance, done using the software PCI Geomatica Orthoengine or other tools. In areas with no sufficient ground control available, such information is directly computed from the given satellite position and rotation angles. In such cases, the line-of-sight for an individual image point is intersected with the Earth ellipsoid. The resulting position on the ellipsoid is corrected for the actual point elevation, which in turn, is estimated from the 3N-3B parallax of the selected GCP. Such GCPs may, then be imported into, for instance, PCI Geomatica for bundle adjustment (Kääb, 2002; Kääb *et al*., 2002).

A number of comparisons to aero-photogrammetrical DTMs were performed to evaluate ASTER DTMs. It turned out that under difficult high-mountain conditions with high relief, steep rock walls, deep shadows and snow-fields without contrast, severe errors of up to several hundred meters occur in the ASTER DEM, especially for sharp peaks with steep northern slopes. These errors are, to some extent not surprising, keeping in mind that such northern slopes are heavily distorted (or even totally hidden) in the 27.6 back-looking band 3B, and lie, at the same time, in shadow. The RMS error for such terrain is in the order of several tens of meters. For more moderate mountainous terrain, RMS errors on the order of 10 - 30 m were achieved, i.e. in the order of the spatial resolution of applied ASTER VNIR data (Figure 2) (Kääb *et al*., 2002).

The availability of SRTM DEMs provides an additional source of topographic information that may be used in some regions. Stereo methods are needed above 60º latitude. In high-relief alpine regions, SRTM spatial coverage may be limited due to radar shadows. In the western Himalaya, for example, SRTM spatial coverage accounts for approximately 75 percent of the needed coverage. This potentially reduces the effective use of SRTM data in some mountain areas. In addition, some regions exhibit rapid topographic changes due to catastrophic processes and high-magnitude surface processes. Glacier surface changes also occur. Consequently, the lack of SRTM repeat coverage represents another limitation that can be overcome using stereo methods.

Laser altimetry is a relatively new approach for acquisition of accurate topographic information. Unfortunately, rugged alpine

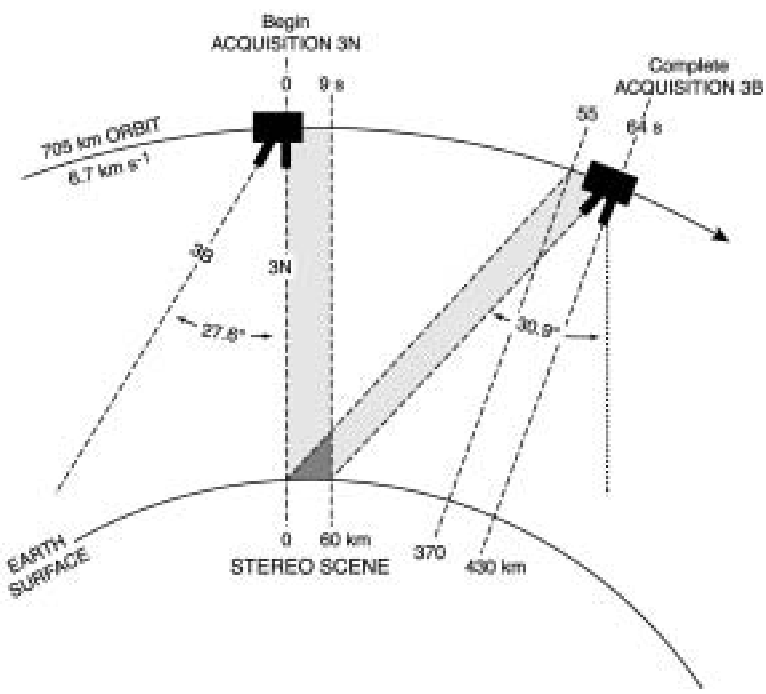

Figure 1 ASTER stereo geometry and timing of the nadir-band 3N and the back-looking sensor 3B. An ASTER nadir scene of approximately 60 km length, and a correspondent scene looking back by 27.6º off-nadir angle and acquired about 60 seconds later, form, together, a stereo scene. After ERSDAC (1999a, b) and Hirano et al. (2003).

environments create limitations. Future satellite laser systems, however, promise great improvements in obtaining altimetry, surface albedo, and other biophysical information.

Anisotropic-Reflectance Correction

Earth scientists working with satellite imagery in rugged terrain must correct for the influence of topography on spectral response (Smith *et al*., 1980; Proy *et al*., 1989; Bishop and Colby, 2002). The literature refers to this as the removal or reduction of the *topographic effect* in satellite imagery, and it is generally referred to as topographic normalization (e.g., Civco, 1989; Colby, 1991; Conese *et al*., 1993a; Gu and Gillespie, 1998). Numerous environmental factors such as the atmosphere, topography and biophysical properties of matter govern the magnitude of the surface irradiance and upward radiance. Other factors such as solar and sensor geometry are critical, such that the magnitude of the radiant flux varies in all directions (anisotropic reflectance).

From a perspective of physical modeling, the problem is one of characterizing anisotropic-reflectance variations, as environmental factors govern the irradiant flux and the bi-directional reflectance distribution function (BRDF). From an applications point-of-view, anisotropic-reflectance correction (ARC) of satellite imagery is required to accurately map natural resources and estimate important land-surface parameters (Yang and Vidal, 1990; Colby and Keating, 1998; Bishop *et al*., 2003; Bush *et al*., 2004).

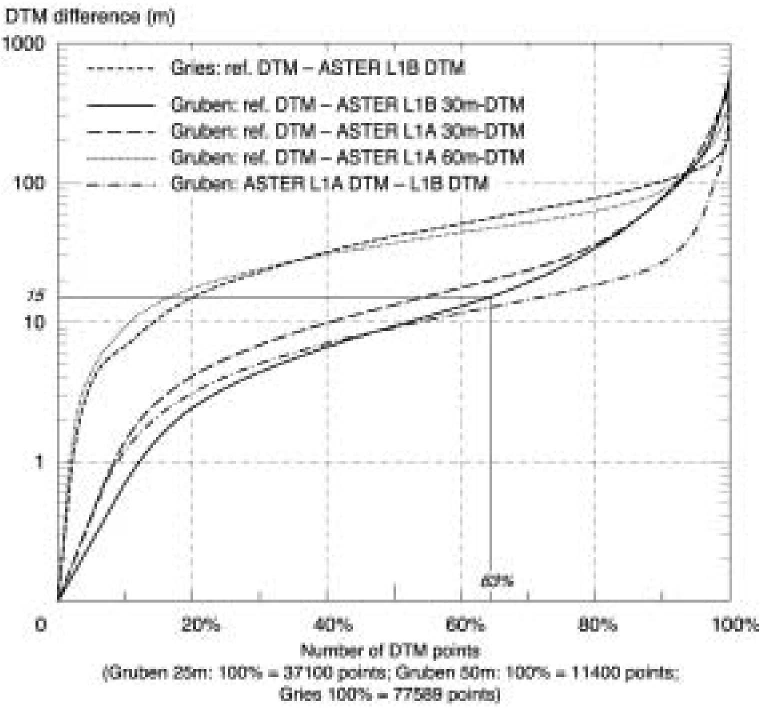

Figure 2 Cumulative histogram of absolute deviations between areo-photogrammetric reference DTMs and ASTER L1A or L1B derived DTMs. For the ASTER L1B derived DTM of the Gruben area, for instance, 63 percent of the points show a deviation of ±15 m or smaller, the ASTER VNIR pixel size. The Gruben site shows extreme high-mountain characteristics with high relief (1500-4000 m a.s.l.), sharp peaks and ridges, and steep flanks. The area contains only a small fraction of glacier-accumulation areas. The glacier tongues are usually debris-covered. Both facts result in a comparable high optical contrast in the applied imagery. The second test site, the Gries area, is a more moderate mountain area. Optical contrast is, however, worse due to large snow-covered and clean ice areas. Gross errors for the Gries area ASTER DTM are, therefore, reduced but the overall accuracy is worse compared to the Gruben area. Both test sites are situated in the Swiss Alps.

Research into this problem has been ongoing for about twenty years. To date, an effective ARC model to study anisotropic reflectance in mountain environments has yet to emerge (Bishop and Colby, 2002; Bishop *et al*., 2003).

Various approaches have been used to reduce spectral variability caused by the topography. They include: 1) spectral-feature extraction – various techniques are applied to satellite images and new spectral-feature images are used for subsequent analysis; 2) semi-empirical modeling – the influence of the topography on spectral response is modeled by using a DEM; 3) empirical modeling – empirical equations are developed by characterizing scene-dependent relationships between reflectance and topography, and; 4) physical radiative transfer models – various components of the radiative transfer process are parameterized and modelled using the laws of physics.

The different approaches have their advantages and disadvantages with respect to computation, radiometric accuracy, and application suitability. Spectral-feature extraction and the use of spectral-band ratios and principal components analysis have been widely used (Conese *et al*., 1993b; Ekstrand, 1996).

For many applications, spectral-band ratioing is most frequently used to reduce the topographic effect. It is important, however, to account for atmospheric effects such as the additive path-radiance term before ratioing (Kowalik *et al*., 1983). This dictates that DN values should be converted to radiance, and atmospheric-correction procedures accurately account for optical-depth variations (Hall *et al*., 1989). The altitude-atmosphere interactions are almost never considered, and information may be lost in areas where cast shadows are present because the diffuse irradiance and adjacent-terrain irradiance are not accounted for. One might also expect that ratioing using visible bands may not be effective due to the influence of the atmosphere at these wavelengths. Ekstrand (1996) found this to be the case and indicated that the blue and green regions of the spectrum should not be used for ratioing to reduce the topographic effect. Furthermore, land-surface estimates cannot be directly derived from relative transformed values.

Other investigators have attempted to correct for the influence of topography by accounting for the nature of surface reflectance (Lambertian or non-Lambertian) and the local topography (Colby, 1991; Ekstrand, 1996; Colby and Keating, 1998). Semi-empirical approaches include Cosine correction (Smith *et al*., 1980), Minnaert correction (Colby, 1991), the c-correction model (Teillet *et al*., 1982), and other empirical corrections that make use of a DEM to account for pixel illumination conditions. These models have been widely applied over small areas of limited topographic complexity, given their relative simplicity and ease of implementation.

Research indicates that these approaches may work, only for a given range of topographic conditions (Smith *et al*., 1980; Richter, 1997), and they all have similar problems (Civco, 1989). For example, the Cosine-correction model does not work consistently. Smith *et al*. (1980) produced reasonable results for terrain where slope and solar-zenith angles were relatively low. Numerous investigators have found that this approach "over-corrects" and cannot be used in complex topography (Civco, 1989; Bishop and Colby, 2002).

The Minnaert-correction procedure has been used frequently because it does not assume Lambertian reflectance. It relies on the use of a globally-derived Minnaert "constant" (k), to characterize the departure from Lambertian reflectance. Ekstrand (1996) found the use of one fixed k value to be inadequate in a study in southwestern Sweden, and previous work has suggested that local k values may be needed (Colby, 1991). Over-correction can still be a problem, and this prompted Teillet *et al*. (1982) to propose the c-correction model, where c represents an empirical-correction coefficient that lacks any exact physical explanation. Other empirical models, which are based upon the relationship between radiance and the direct irradiance, have similar problems and are not usable for some applications (Gu and Gillespie, 1998).

Given the popularity of the Minnaert-correction model, Bishop and Colby (2002) tested it in the western Himalaya and found the implementation to be inadequate for large areas exhibiting topographic complexity, because high r^2 values are required for the computation of k. Instead, they used multiple Minnaert coefficients to characterize anisotropic reflectance caused by topography and land cover. Furthermore, they found that ARC can alter the spatially-dependent variance structure of reflectance in satellite imagery.

The aforementioned problematic issues are the result of ignoring the primary scale-dependent topographic effects (Proy *et al*., 1989; Giles, 2001). Previous research has not provided an adequate linkage between topographic, atmospheric and BRDF modeling. Furthermore, the degree of reflectance anistropy is wavelength dependent (Greuell and de Ruyter de Wildt, 1999), and most models do not enable investigation of this important surface property.

It is evident from the literature that a landscape-scale topographic solar-radiation transfer model that enables ARC of satellite imagery and the prediction of parameters of the surface energy budget is needed for glaciological investigations. Furthermore, this GIS-based modeling is required to make progress on automated glacier assessment and mapping from space.

Glacier Mapping

Arctic

The glaciers and ice caps of the Canadian Arctic Islands cover an area of approximately 150,000 km^2 (Ommanney, 1970; Williams and Ferrigno, 2002a). This is the largest area of ice outside of the Antarctic and Greenland ice sheets, and comprises ~ 5 percent of the Northern Hemisphere's ice cover (Koerner, 2002). Of this area, approximately 40,000 km^2 of ice exists on Baffin and Bylot Islands (Andrews, 2002). The Penny and Barnes Ice Caps are the largest on Baffin Island, and are thought to be the final remnants of the Laurentide Ice Sheet. Further to the north, the Queen Elizabeth Islands contain approximately 110,000 km^2 of ice amongst 8 large ice caps and many smaller glaciers on Devon, Ellesmere and Axel Heiberg Islands. The only ice that exists in the western part of the Canadian Arctic Islands are a few small ice caps on Melville Island which total < 160 km^2 in size. A full review of the distribution of glaciers in the Canadian Arctic Islands and history of scientific studies in this region may be found in Williams and Ferrigno (2002b).

The large areas of ice in the Canadian Arctic Islands present a challenge for glacier mapping. To enable efficient determination of ice-covered areas, recent work has focused on evaluating automated techniques to map glacier outlines in Landsat 7 imagery. Techniques developed for other regions are not necessarily directly transferable to the Canadian Arctic due to the lack of vegetation, rare occurrence of debris-covered glaciers, and dominance of large ice caps in this area.

To prepare the imagery for classification, the Landsat 7 ETM+ scenes were first orthorectified using ground control points determined from published 1:250,000 scale maps and 100 m resolution DEMs provided by Geomatics Canada. Once orthorectified, the Landsat scenes were mosaicked to provide a single image of each ice cap in the study area. Late summer imagery from the same or similar acquisition dates was used for this mosaicking, with most scenes coming from July and August 1999. Areas of surrounding sea ice were clipped from these orthomosaics, and three automated classification methods were evaluated for their ability to differentiate ice from non-ice areas in the imagery:

1. Thresholded band 4/band 5 ratio image. This method has been chosen as the core algorithm for the new Swiss glacier inventory (Kääb *et al*., 2002), and has provided good results in some alpine regions. This method provided generally good results for the Canadian High Arctic, except in deeply shadowed areas on glaciers which were often misclassified as being non-ice. In addition, the scheme did not work well for areas with light cloud cover.
2. Unsupervised classification of Landsat 7 band 8 (panchromatic) imagery (Vogel, 2002). Similarly, this method worked well for most areas, but had the problem of misclassifying deeply shadowed areas on glaciers as

non-ice, and also had a tendency to classify small snow patches (e.g., in gullies) as ice. This resulted in very uneven glacier outlines with many small patches. This method, however, was slightly better at classifying ice in areas of light cloud cover than the band 4/band 5 ratio method.

3. Unsupervised classification using the normalized-difference snow index (NDSI) (Dozier, 1984):

$$NDSI = \frac{band2 - band5}{band2 + band5} \quad (1)$$

This method utilizes the brightness of snow and ice in the visible band 2 versus the low reflectivity in the near-infrared band 5 (Vogel, 2002). It performed the best of the three techniques in our study area, successfully classifying most areas that were in shadow, while excluding the small snow patches that were a problem with method 2 (Figure 3a&b). It was also generally effective through areas of thin cloud, and was therefore chosen as the best technique for our needs.

To create the final glacier outlines for GLIMS, the classified raster output from the NDSI method was first passed through an eliminate filter to remove small patches less than 0.1 km^2 in size. It was then passed through despeckle and sharpen filters to remove noise, and manually checked against the original Landsat 7 imagery. Although NDSI provided the best results of the three methods, it was still necessary to correct the ice-covered areas in some areas where there was heavy shadowing or the surface was waterlogged. The final, cleaned raster image was converted to vector shapefiles in ArcView (Figure 3c). The ice-cap outlines were then subdivided into individual drainage basins using the DEM discussed above. These form the basic unit of input to the GLIMS database, and facilitate the derivation of characteristics for individual basins such as length, hypsometry, area, etc.

Future work will involve an assessment of the changes in ice extent over the last 40 years. A complete set of high resolution aerial photographs was flown over the Canadian Arctic in 1959/60, which will provide a basis for quantifying glacier changes when compared with the present day Landsat 7 imagery. Initial calculations suggest that small ice caps such as those on Melville Island have reduced in area by as much as 20 percent over this time, although the percentage area changes are much lower on the large ice caps.

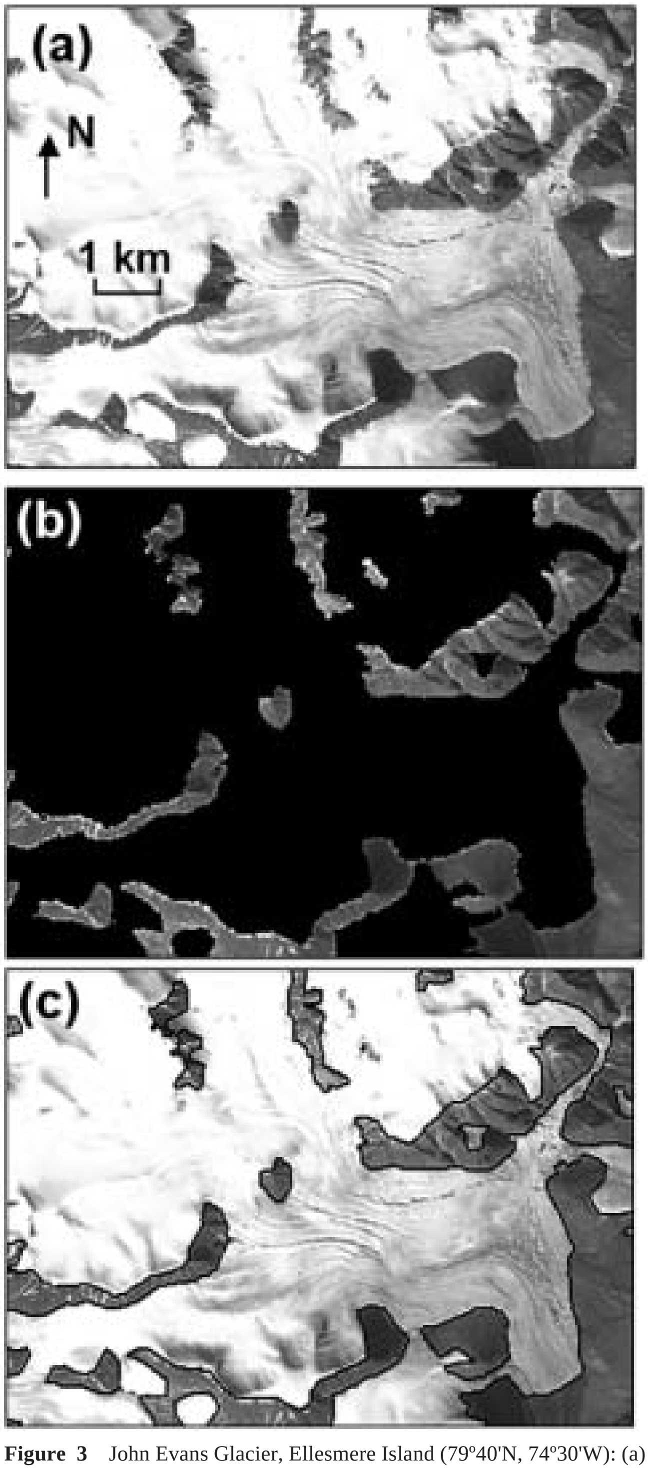

Figure 3 John Evans Glacier, Ellesmere Island (79º40'N, 74º30'W): (a) Original Landsat 7 imagery; (b) Imagery classified into ice and non-ice areas using the NDSI classification method; (c) Final ice outlines superimposed on the original Landsat 7 imagery.

Alaska

More than 95 percent of the estimated 100,000 glaciers in Alaska have retreated since the late nineteenth century. The rate of glacier-volume decrease has been accelerating, with the recent rate of volume loss about three times greater during the period since 1995, compared with the period 1950 to 1995 (Arendt *et al.*, 2002). This accelerating rate of loss has made Alaska glaciers the largest single glaciological contributors to rising sea level during the past 50 years (Arendt *et al.*, 2002). Glacier volume losses in Alaska are linked to climate warming during the past several decades (IPPC, 2001) with complications added by surging and calving dynamics. Deglaciated terrains present new hazards by exposed steep valley walls that are susceptible to mass failures and by forming new glacier-dammed lakes that almost invariably outburst and flood downstream valleys.

Volume changes of only 67 glaciers in Alaska have been evaluated; all from laser profiling data (Arendt *et al*., 2002). Long-term mass balance studies on 5 of these glaciers (Hodge *et al*., 1998;Rabus and Echelmeyer, 1998; Pelto and Miller, 1990; Miller and Pelto, 1999) corroborate the accelerating rates of mass loss during the past decade. On Gulkana Glacier, in the central Alaska Range, a photogrammetric volume change (geodetic) analysis for the periods 1974-93 and 1993-1999 (Figure 4) confirmed both the laser-profile and cumulative surface mass balance (glaciologic) results. The two periods of analysis show that the glacier-wide rate of loss increased from 0.3 meters of water per year between 1974 and 1993, to 0.9 meters of water per year between 1993 and 1999. Gulkana Glacier is one of two benchmark basins in Alaska that serve as reference data for remote sensing and GIS analyses. Most of the rest of the trend in glacier-volume reduction has been deduced from geologic evidence of terminus changes, discovery-era mapping, and more recently from early terrestrial and aerial photographic documentation. Remote sensing and GIS inventorying and analysis of glaciological trends is underway.

An example of Alaskan glacier mapping in the area of upper College Fiord, Prince William Sound, has been conducted (Figure 5). Supervised classification was used with five categories of training sites including water, vegetated slopes, bare bedrock, moraine-covered and debris-covered ice, and exposed ice (Figure 6). This preliminary work was designed to compare ground-based and aerial observations of the imaged area with the ASTER classification to determine classification accuracy.

The classified area has been studied and photographed on many occasions during the past 30 years. Near-vertical aerial photographs of two locations, the terminus and lower reaches of Smith Glacier (Figure 7), and the terminus and lower reaches of Yale Glacier (Figure 8) were selected for comparison with the classified image.

For the Smith Glacier, from southwest to northeast, the classified image of the terminus and lower reaches of the glacier (Figure 6) shows an apron of debris-covered ice, then a triangle of bare rock, a band of debris-covered ice, a band of exposed ice, a second band of debris-covered ice, a second band of exposed ice, a third band of debris-covered ice, an irregularly-shaped area of bare bedrock, and a fourth thin band of debris-covered ice. All of these are sandwiched between two vegetated slopes.

The September 3, 2002 oblique aerial photograph of the terminus and lower reaches of Smith Glacier (Figure 7), shows a different and more complicated picture. Much of the apron of debris-covered ice is actually glacially-derived sediment suspended in the surface waters of College Fiord and pieces of floating brash ice. In other places, what is classified as debris-covered ice is till and glacial-fluvial sediment. The triangle of bare rock (Figure 7) is a large area of till and glacial-fluvial sediment, a braided stream and its delta, and a crescent-shaped wedge of vegetation. The band of debris-covered ice, the band of exposed ice, the second band of debris-covered ice, the second band of exposed ice, and the third band of debris-covered ice are correctly classified. Far more bare ice is present, however, than is indicated by the classification. The irregularly-shaped area of bare bedrock does correspond to a recently exposed bedrock barren zone, but it also includes a large area of till and glacial-fluvial sediment. The fourth thin band of debris-covered ice is actually a continuation of the large area of till and glacial-fluvial sediment.

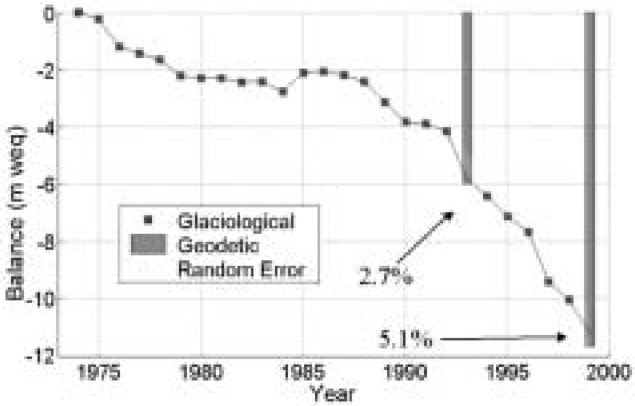

Figure 4 Cumulative surface mass-balance measurements of volume change (the glaciologic series) on Gulkana Glacier, in the central Alaska Range, Alaska, agrees within a few percent of the geodetic determinations of the change in glacier volume measured between 1974 and 1993 and between 1993 and 1999. Glaciologic measurements on Gulkana Glacier began during 1962.

For the Yale Glacier, the classified image of the terminus and lower reaches (Figure 6) is far more complicated than the classified image of the terminus and lower reaches of Smith Glacier. From southwest to northeast, the image shows a vegetated slope, a band of debris-covered ice, an irregularly-shaped mass of bare rock with several linear areas of debris-covered ice, a band of debris-covered ice with a linear area of vegetation, a large band of exposed ice, and an area of firn.

As was the case with Smith Glacier, the September 3, 2002 oblique aerial photograph of the terminus and lower reaches of Yale Glacier (Figure 8), shows different and more complicated patterns. From southwest to northeast, the image depicts a vegetated slope, then a triangular-shaped lake filled with suspended-sediment-laden water rather than a large band of debris-covered ice. To its east is an irregularly-shaped mass of hummocky bedrock with a number of blue-water lakes and several areas of vegetative cover, but no debris-covered ice. To its east is a narrow band of debris-covered ice and then a large band of exposed ice. Its eastern side is heavily crevassed and bordered by a band of debris-covered ice. No area of firn is present on the eastern margin.

The data indicate that the supervised classification successfully recognizes many large general classes of features, but has a difficult time discriminating detail beyond the limits of the spatial resolution of the sensor and between similarly-reflective features. Perhaps selection of more narrowly defined training sites and the use of additional spectral and spatial features may produce better classification

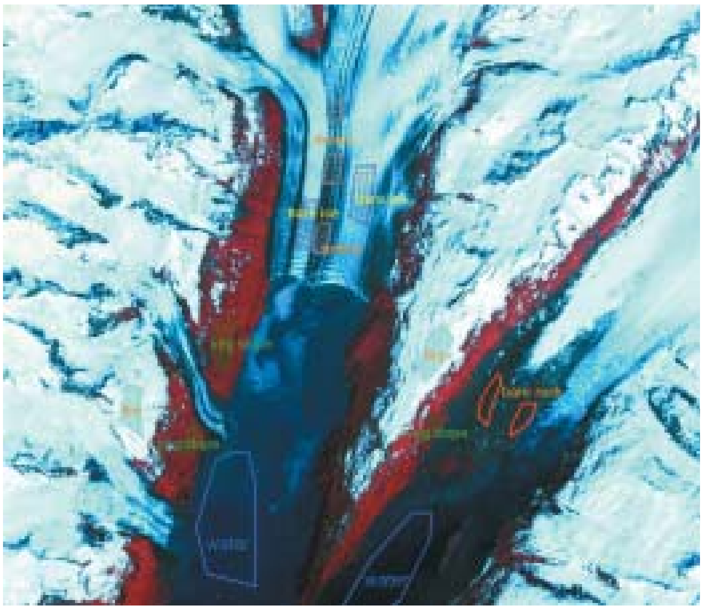

Figure 5 ASTER VNIR false-color composite (321 RGB) image of upper College Fiod, Prince William Sound, Alaska. Shown on the image are the lower reaches of the advancing Harvard Glacier, the retreating Yale Glacier, and most of Smith, Bryn Mawr, and the northern part of Vasser Glaciers. Five categories of training sites are shown: water, vegetated slopes, bare bedrock, moraine-covered and debris-covered ice, and exposed ice.

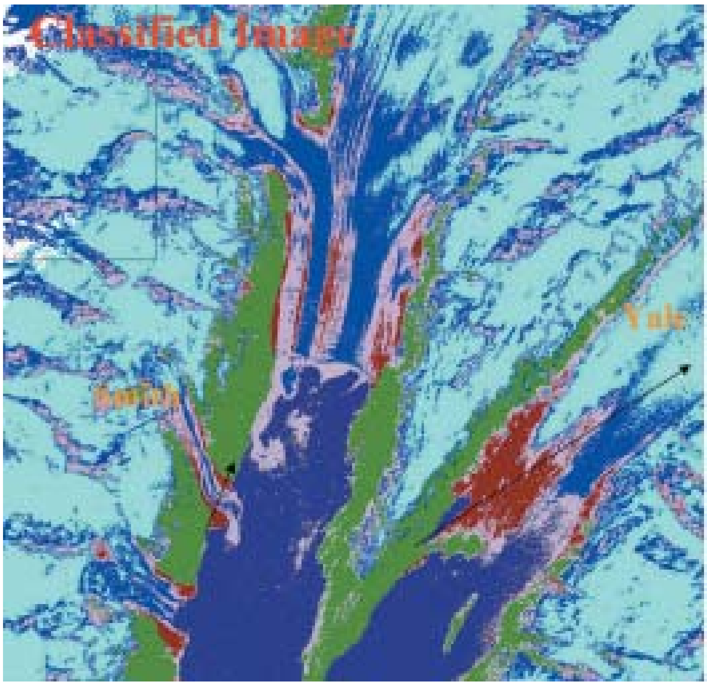

Figure 6 A supervised classification of the ASTER data presented in Figure 5. The black lines shows the direction and extent of photography (Figures 7 & 8) being compared to the classification results.

accuracies. Therefore, additional information and/or approaches to image classification of Alaskan glaciers are needed to address spectral similarities associated with supraglacial debris cover (Bishop *et al*., 2000, 2001; Kääb *et al*., 2002).

American West

Scientific study of the glaciers in the American West (exclusive of Alaska) did not begin until September 1871 when glaciers were first “discovered” on Mt. Shasta, California by the King Expedition sponsored by the War Department (King, 1871). On that same expedition separate parties identified glaciers further north on Mt. Hood in Oregon and Mt. Rainier in Washington.

Glaciers in the American West span the latitude of 37º to 49º N and longitude from 105º to 124º W. They occur in the states of Colorado, Wyoming, Montana, Idaho, Utah, Nevada, Idaho, California, Oregon, and Washington. Only six states have appreciable glacier cover (Colorado, Wyoming, Montana, California, Oregon, and Washington), whereas the others have dubious claims to glaciers that may be perennial snow patches (Figure 9). According to Meier and Post (1975),

Figure 7 September 3, 2002, oblique aerial photograph of the terminus and lower reaches of Smith Glacier. Photograph by Bruce F. Molnia.

Figure 8 September 3, 2002, oblique aerial photograph of the terminus and lower reaches of Yale Glacier. Photograph by Bruce F. Molnia.

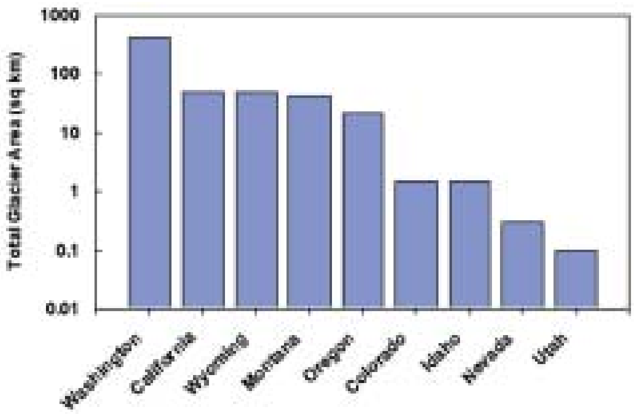

Figure 9 Bar chart showing the total glacier-covered area in each state (Meier and Post, 1975).

Figure 10 Photograph of Middle Cascade Glacier, North Cascades Range, Washington.

glaciers cover about 587.4 km^2 of the American West as of about 1960, of which about 71 percent are located in Washington State and are small alpine glaciers. The largest is Emmons Glacier on Mt. Rainier, at 11.2 km^2. The average size of a glacier (those that exceed 0.1 km^2) in the North Cascades National Park, one of the most heavily glaciated regions of the west, is 0.37 km^2 (Granshaw, 2001).

Glacier altitudes rise with decreasing latitude with warmer climates to the south (Meier, 1961). Glacier altitudes also rise with distance from moisture sources. For example, Post *et al*. (1971) and Granshaw (2001) showed that for the North Cascades of Washington, average glacier elevation increases eastward away from the Pacific Ocean. Generally speaking the glaciers in the northwestern part of the US West are more numerous and exist at lower elevations (~ 2000 m) compared to glaciated areas in the drier regions to the southeast (Wyoming, Colorado) and the warmer regions to the south (California), ~ 3000 m. Montana, which is drier and cooler than the Northwest, has glaciers at altitudes ~ 2500 m. Consequently, the Northwest hosts true valley glaciers, particularly on the stratovolcanoes, which present some of the highest accumulation zones in the region. Glaciers in the other regions tend to be more mountain glaciers where the ice terminates on the mountainside, never making it to the valley below. In the southern regions of California and Colorado the glaciers are largely cirque glaciers.

In the past few decades the glaciers have been receding (Marston *et al*., 1991; McCabe and Fountain, 1995; Dyurgerov and Meier, 2000; Hall and Fagre, 2003), continuing a trend from the Little Ice Age (Davis, 1988; O'Connor *et al*., 2001). The magnitude of area shrinkage varies. For the North Cascades National Park (Washington), between 1957 and 1997 the shrinkage of 321 glaciers averaged 7 percent (Granshaw, 2001). For about the same period of time in Glacier National Park (Montana) the shrinkage for two glaciers was about 33 percent (Hall and Fagre, 2003). This range in values seems to be broadly consistent with changes elsewhere in the west.

Detailed measurements of glacier mass balance are available only from South Cascade Glacier, located in the North Cascades of Washington (Figure 10). Variations in net mass balance are positively correlated with the mass balance of other glaciers in the region although the amplitude of the change may differ (Granshaw, 2001). South Cascade has been generally losing mass and retreating since 1958 (Krimmel, 1999). The mass loss accelerated starting in 1976 due to a change in atmospheric circulation patterns which reduced winter snow accumulation (McCabe and Fountain, 1995). This trend is reflected in the global trend of mass balance variation (Dyurgerov and Meier, 2000) and we presume the variations in glacier mass of the American West is similar. One notable exception to this trend is the rapidly growing glacier in the crater of Mt. St. Helens. It has gained 900 percent in area (0.1 to 1.0 km^2) in 5 years (Schilling *et al*., 2004). This unusual exception is due to the eruption of Mt St. Helens in 1980, which created a deep north-facing crater, ideal conditions for collecting and protecting a seasonal snow cover.

Assessment of glacier change in the American West has been sporadic since the start of scientific observations in the 1930's. Part of the challenge has been the inaccessible nature of the glaciers, which makes repeated observations difficult over sustained periods. In the late 1950's, a series of mass balance programs were initiated at Blue Glacier (Armstrong, 1989) and South Cascade Glacier (Meier and Tangborn, 1965). Since that time other programs measuring various glacier variables have come and gone. It is essential to maintain mass-balance programs in this region to validate remote sensing/GIS glacier studies before South Cascade Glacier and others disappear.

The glaciers of the AmericanWest are distributed across thousands of kilometers, consequently glacier information is also widely distributed. To help organize this information, we are developing an additional regional GIS database for assessing glacier distribution and glacier change. Our GIS relies on historic topographic maps (1:63,360 or 1:24,000) to populate the database with one complete depiction (extent and topography) of each glacier in the west. The maps were produced by the US Geological Survey, based on aerial photography of the late 1950's. Where available, glacier extents and topography from other historic maps are added. Some federal agencies have conducted special mapping efforts and/or arranged long-term glacier monitoring efforts (e.g., National Park Service). Current and future updates to the database will be derived from satellite imagery. An important attribute of this database is that it is available via the World Wide Web (www.glaciers.us).

The GIS database is only part of a glacier-monitoring strategy that includes detailed ground-based, mass-balance measurements at a few glaciers and less detailed measurements at other glaciers (Fountain *et al*., 1997). Taken together, the GIS database provides a regional to continental-scale context of glacier change, whereas the detailed surface-based measurements provide specific information on the physical processes and seasonality controlling glacier change.

The future of assessing glacier change in the west will rely on satellite remote sensing. Accurate mapping and assessment, however, is a challenge given the small size of the glaciers (e.g., 0.37 km^2 in the North Cascades) and mapping limitations because of spatial resolution. The relatively coarse systems of the past were not suitable for monitoring glacier changes. The more recent systems, such as SPOT, Ikonos, ASTER, and Landsat-7 ETM+, provide spatial resolutions of 15m or less and are better suited for the glaciers of the west. Unfortunately, in many situations around the world, the spatial resolution may be too coarse, which precludes tracking the small glaciers or glacier changes over short time intervals. With the recent advent of high-resolution imagery (Ikonos), the problem of spatial resolution is solved, however, the added spectral variability poses new problems.

Switzerland

Landsat TM data have widely been used for glacier mapping using a variety of different methods (Williams and Hall, 1998; Gao and Liu, 2001). Apart from manual glacier delineation by on-screen cursor tracking, most methods utilize the low reflectance of ice and snow in the middle-infrared part of the spectrum for glacier classification. The methods used range from thresholded ratio images (Bayr *et al*., 1994; Jacobs *et al*., 1997), to unsupervised (Aniya *et al*., 1996) and supervised (Li *et al*., 1998) classification, to principal components (Sidjak and Wheate, 1999) and approaches using fuzzy set theory (Binaghi *et al*., 1997; Bishop *et al*., 1999). Comparisons for the same test region suggest that thresholded TM4 / TM5 ratio images using original digital number (DN) values, produce reasonable results with respect to accuracy (Hall *et al*., 1989; Paul, 2001). Moreover, band ratioing can also be used with other satellite data with similar spectral bands (e.g., ASTER, IRS-1C/D, SPOT 4/5). Consequently, the method was chosen as the core algorithm for the new Swiss glacier inventory (Kääb *et al*., 2002).

Thresholding ratio images is most sensitive in regions with ice in cast shadow, where the threshold value (in general around 2.0) should be selected. Application of a median filter to the final glacier map reduces noise considerably. Turbid lakes and vegetation in cast shadow are also missclassified as glacier ice from TM4 / TM5. They can, however, be excluded from the glacier map by performing a separate classification and doing overlay GIS operations. At low sun elevations (high latitudes or late autumn) TM3 / TM5 gives better results for glacier areas in shadow, but more turbid lakes are incorrectly mapped. A hierarchical, ratio-based method (Wessels *et al*., 2002) can be used as an alternative for mapping supraglacial lakes. For icecaps (i.e., no cast shadows) which are covered by a thin volcanic ash layer (e.g., Vatnajökull), the thermal infrared band TM6 can be used instead of TM5.

The main problem for rapid, automatic glacier mapping is debris cover on ice, because supraglacial debris typically has the same spectral properties as the surrounding terrain (lateral moraines, glacier forefields, etc.) and must frequently be delineated manually. Paul *et al*., 2004 proposed a method for mapping debris-covered glaciers by combining multispectral and DEM classification techniques using GIS-based processing. For the new Swiss glacier inventory, TM-derived glacier maps are converted from raster to vector format, and individual glaciers are obtained by intersection with manually digitized glacier basins. Three-dimensional glacier parameters are derived from DTM fusion (Figure 11) .

Remote sensing and GIS investigations of the Swiss Alps indicate the following general findings:

- Changes in glacier geometry are highly individual and non-uniform. Thus, only a large sample of investigated glaciers reveals ongoing changes with a sufficient confidence level.
- Relative changes in glacier area depend mostly on glacier size with an increasing scatter towards smaller glaciers. Thus, the size classes used for area change assessments have to be noted.
- The area of ice-mass loss has been found to be due to separation of formerly connected tributaries and emerging rock outcrops and shrinkage along the entire glacier perimeter (including accumulation area), rather than due to classical glacier tongue retreat. These facts clearly point to a strong down-wasting trend of the Swiss glaciers.
- The way of calculating new glacier parameters after changes in geometry or length is not yet defined. Thus, the definition of new and GIS-adapted standards is required in the future.

More specific results of glacier change for the Swiss Alps are derived from the 1973 inventory (Figure 12) and Landsat TM imagery:

- The relative loss in glacier area from 1973-1998/9 is about -20 percent, with only little changes until 1985 (-1 percent) and a loss of about -10 percent for each period 1985-1992 and 1992-1998/9.
- Glaciers smaller than 1 km^2 contribute about 40 percent to the total loss of area from 1973 to 1998/9, although they cover only 15 percent of the total area in 1973.
- The highest absolute loss of area with elevation is found where most glaciers are located (around 2800 m asl), while highest relative changes occur at lower elevations (below 2000m asl).

The experience gained from the new satellite-data derived Swiss glacier inventory suggests that inventory of global glaciers from TM or ASTER data in a GIS environment is possible and able to generate new insights in the characteristics of land-ice distribution and its changes with time. Careful pre-processing such as orthorectification or delineation of debris-covered ice is required to ensure quality results.

Western Himalaya

The Himalaya represents a significant region which includes central Asia, Afghanistan, Pakistan, and the Indian and Nepalese Himalaya. This “critical region” is thought to contribute 16 percent of the water transferred to the world’s oceans (Haeberli, 1998). Little is known about the glaciers in the western Himalaya and Hindu Kush, although among the first remote sensing and glacial geomorphological studies were conducted by Shroder (1980, 1989); Bishop *et al*. (1995, 1998a,b, 1999); Shroder and Bishop (2000); Shroder (2004a,b). The western Himalaya and Hindu Kush region lacks fundamental and reliable glaciological information, although a number of workers in recent decades have contributed essential fieldwork and surveys of available literature (Horvath, 1975; Mercer, 1975b,a; Mayewski and Jeschke, 1979; Mayewski *et al*., 1980; Goudie *et al*., 1984; Hewitt and Young, 1990).

Our field investigations and remote sensing analyses

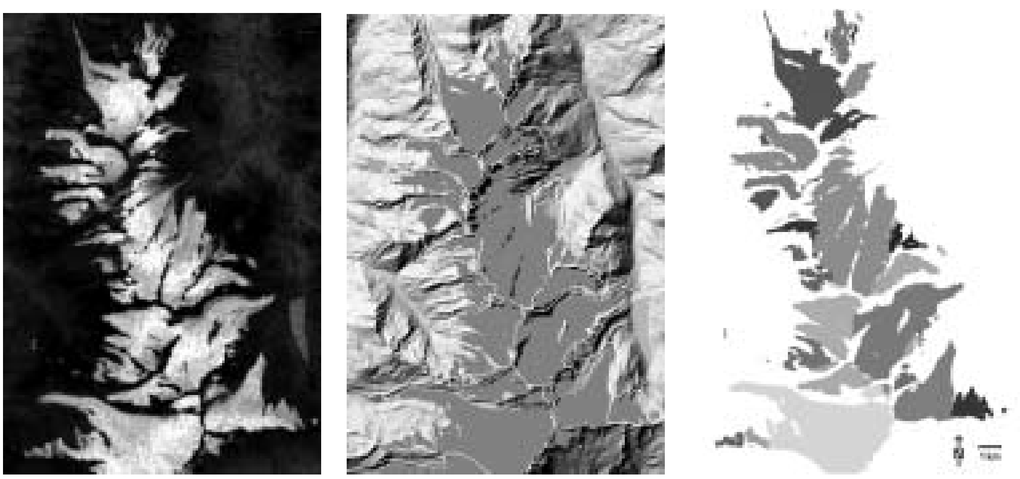

Figure 11 A ratio image (left) obtained from TM4 / TM5 is converted to a glacier map by thresholding. GIS-based intersection with digitized glacier basins (middle) extracts individual glaciers, which are combined with a DTM to obtain 3-D glacier parameters (right).

indicate that many of the glaciers are retreating and downwasting. It is not currently known, however, what the regional mass-balance trend is, like many other regions, although field evidence currently suggests a negative mass-balance trend corroborated by mass balance estimates within the larger Himalaya region (e.g., Cao, 1998; Aizen *et al*., 1997; Fujita *et al*., 1997; Bhutiyani, 1999; Meier *et al*., 2003). We do not, however, know the exact number of alpine glaciers within this region, the size distribution, regional ice volume, modern-day and historical spatial-distribution patterns, or the sensitivity of these heavily debris-covered glaciers nearly as well as the eastern Himalaya (e.g., Mool *et al*., 2001a,b). This information is critical for understanding the variability in climate and ice-volume fluctuations, as this region has experienced significant climatic variations and glacial fluctuations (Phillips *et al*., 2000; Shroder and Bishop, 2000; Bishop *et al*., 2002).

Numerous studies have indicated the difficulty of addressing the problem of glacier mapping in the presence of supraglacial debris cover (e.g., Bishop *et al*., 1995, 2000, 2001; Williams *et al*., 1997; Kääb *et al*., 2002). As we have already indicated, the use of spectral features and per-point classification algorithms is problematic, and this has prompted many to investigate the use of topographic information, as many alpine glaciers exhibit unique topography and boundaries that can be delineated using a DEM.

In the Himalaya, the common topographic complexity dictates a sophisticated treatment of spectral and topographic analysis in order to map glaciers (Bishop *et al*., 2000, 2001). This has led to the development and testing of an object-oriented glacier mapping model that uses data modeling and analysis of the topography to characterize and map debris-covered alpine glaciers.

First- and second-order geomorphometric parameters (i.e., slope, slope aspect, curvature) serve as the basis of this approach. Using a topology of elementary forms, which is based upon the integration of the terrain parameters, elemental terrain-form objects can be generated (Bishop *et al*., 2001). The geometric attributes and 3-D spatial topological relationships for, and among, these terrain-form objects are then computed. Following hierarchy theory, terrain-form objects are aggregated to identify terrain-feature objects, which are subsequently aggregated to generate landform-feature objects, that can be aggregated to generate other landform-objects.

Bishop *et al*. (2001) discussed the importance of characterizing the hierarchical nature of mountain topography as it relates to surface processes and glacier mapping. They also demonstrated the ability to recognize and characterize process-form relationships, and were able to accurately delineate and map alpine glaciers using a DEM. The hierarchical modeling of the topography in the Himalaya is an important step in understanding topographic forcing on surface processes, and in identifying the operational scale of glaciation on

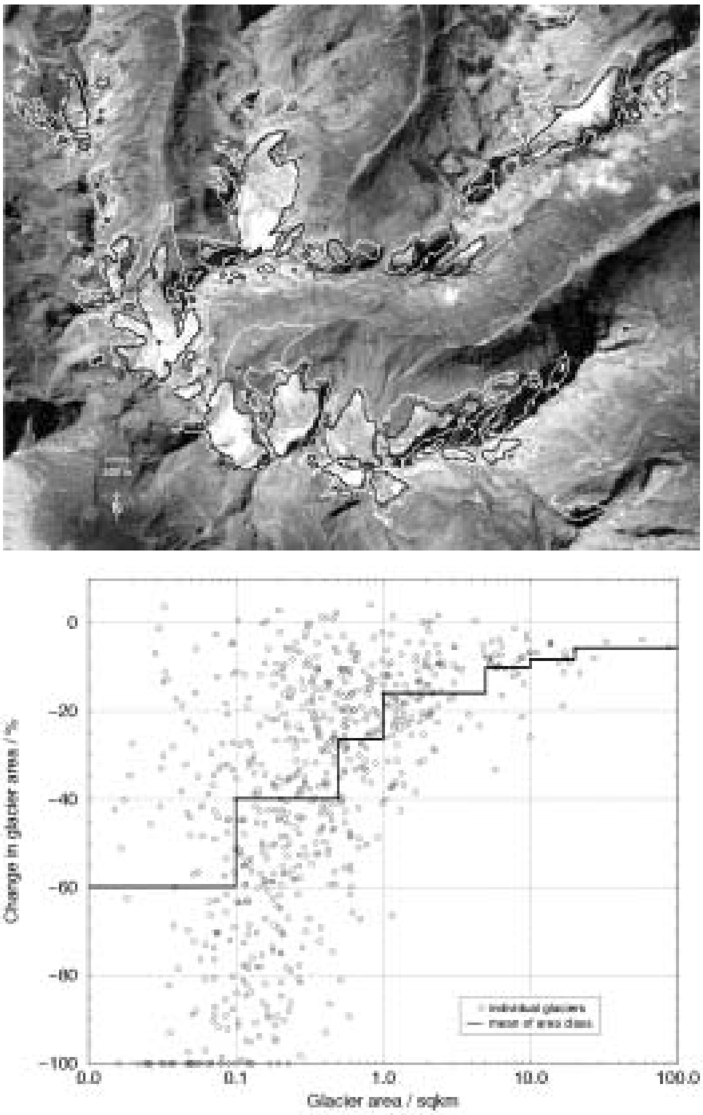

Figure 12 Glacier retreat from 1973 (white) to 1999 (black) is highly individual and non-uniform (exemplified here for the Rheinwald group, Swiss Alps). Also the scatter plot depicts the high variability of relative area changes for glaciers smaller than 1 km^2, as well as an increasing relative area loss towards smaller glaciers if distinct area classes are used.

the landscape (Bishop *et al*., 2001). The advanced analysis enables morphometric, and morphogenetic information to be accounted for, and this type of mapping model works very well for complex debris-covered glaciers in the Himalaya (Figure 13). Additional work is required to address the subtle variations in topographic form to better delineate some parts of a glaciers terminus or boundaries where smooth elevation transitions exist. The addition of shape analysis and 3-D topological analysis is expected to improve the accuracy.

Ultimately, object-oriented analysis of image-derived, land-cover and terrain-objects should enable accurate mapping of debris-covered glaciers. Accurate area estimates are essential for the production of ice volume estimates, as scaling analysis and mass and momentum conservation equations show that glacier volumes are related by a power law to easily measured glacier

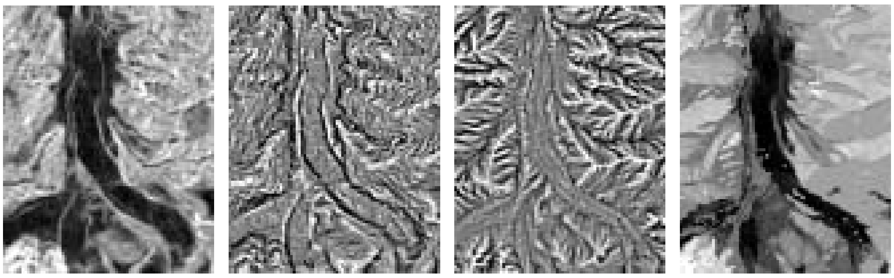

Figure 13 Geomorphometric parameters and object-oriented glacier mapping for the Raikot Glacier at Nanga Parbat. The images from left to right are: 1) slope-angle map, 2) profile-curvature map, 3) tangential-curvature map, 4) automated, glacier-delineation map. Geomorphometric parameters can be used to delineate debris-covered glaciers, and the mapping model does a reasonable job in identifying and delineating the majority of the ablation zone. Problem segments of the glacier boundary can be addressed using advanced 3-D spatial analysis.

surface areas (Bahr *et al*., 1997). Consequently, scaling functions can be used to estimate total ice volume and changes in ice volume.

Mapping Error

As satellite sensors become more sophisticated and the resolution of the resulting imagery increases, the accuracy of measuring glacier changes from space has increased (Hall *et al*., 2003). This applies both to the measurement of changes in glacier terminus and area as well as to the measurement of the glacier facies. The measurement accuracy depends on the registration technique (if the data are not geocoded), and the pixel resolution of the sensor when two satellite images are used.

It is sometimes difficult to measure accurately the position of a glacier terminus from space as was demonstrated by Williams *et al*. (1997), in a study of outlet glacier changes of Vatnajökull, Iceland, using Landsat data. When a glacier is in recession, debris may collect on the surface of part, or all of the glacier tongue, and the glacier will have a spectral reflectance similar to the surrounding moraine. This can make the exact terminus difficult to locate, using spectral and topographic data. On the ground, the terminus position can usually be determined by digging into the top layers of the debris to detect ice below, but this is a very labor-intensive activity. Even if ice is found, it may not be part of the glacier and this stagnant ice, unconnected to the glacier tongue, may further confuse the determination of the terminus.

Advancing glaciers, and other receding glaciers, such as tidewater glaciers with clean termini, are generally easier to measure from space (Sturm *et al*., 1991; Hall *et al*., 1995). Even, however, on receding glaciers with copious amounts of surficial morainal material, such as occurs on the Pasterze Glacier, Austria, good results can still be obtained. For example, in a study of the Pasterze Glacier, between 1976 and 2001, Landsat-derived measurements show a recession of the terminus of the Pasterze Glacier of 479 ± 136 m while measurements from the ground showed a recession of 428 ± 1 m (Hall *et al*., 2003). Figure 14 shows a Landsat image from 2001 with the 1976 and 2001 positions of the Pasterze Glacier terminus shown as derived from Landsat measurements. Though part of the terminus was debris-covered, the calculated uncertainty (±136 m) of the satellite measurement was greater than the difference between the satellite and ground measurement.

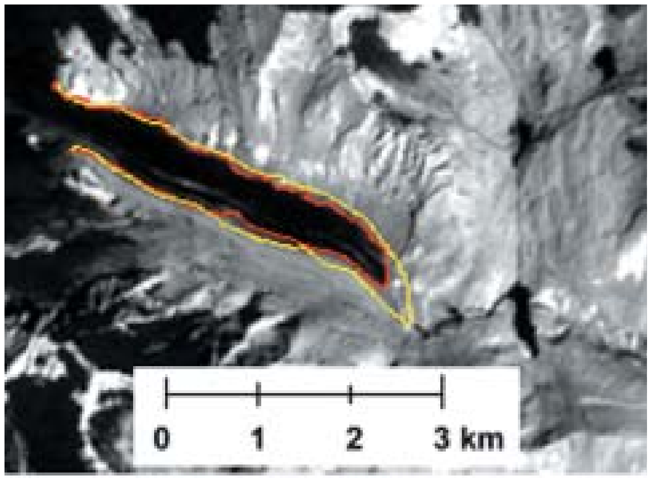

Figure 14 ETM+ band 5 (1.55-1.75 m) image from August 23, 2001, showing changes in the position of the exposed ice part of the Pasterze Glacier tongue from 1976 (yellow line), to 2001 (red line) (Hall *et a*l., 2003).

The Landsat database, beginning in 1972, enables decadal-scale glacier changes to be measured with increasing detail, and is an important resource for measuring glacier changes and correlating those changes with regional climate changes in most glacierized areas on the Earth. With the 1999 launch of the Landsat-7 satellite with the Enhanced Thematic Mapper Plus (ETM+) on board, the resolution available from the Landsat sensors ranged from 80 m (from the early Multispectral Scanner (MSS) sensors) to 30 m (from the Thematic Mapper (TM) and ETM+ sensors) and even 15 m (with band 8 (0.52 - 0.9µm) on the ETM+). The regularly-acquired data from the Landsat series (Bindschadler *et al*., 2001) are especially valuable for studying glacier changes for climate studies.

The ASTER sensor onboard Terra has acquired 15-m resolution multispectral data since early 2000 (Bishop *et al*., 2000; Raup *et al*., 2000). The ability to produce a DEM using data from the ASTER sensor makes it even more valuable for studies of some glaciers, as topographic data is useful for accurate determination of boundaries of debris-covered glaciers (Bishop *et al*., 2000, 2001; Paul *et al*., 2004). Ikonos data, geocoded and with 4-m and 1-m resolution, provide the capability for studying changes with greater precision between years, and are especially suited for detailed mapping of the glacier tongue. Table 1 shows the improvement in accuracy using increasingly advanced satellite-borne sensors and geocoded imagery from the Landsat MSS in 1972, to the present (Hall *et al*., 2003).

High-quality aerial photographs represent additional important information for measuring glacier changes, however, accurate registration and quantitative comparison of aerial photographs and satellite imagery are often difficult, making the associated errors large or unknown. In addition, when an old topographic map and a satellite image are co-registered, it is useful to infer the changes in terminus position and areal extent over time, but it is not possible to determine the accuracy if the accuracy of the original map is unknown. Also, topographic maps can be used to infer present and past positions of the equilibrium-line altitude (Leonard and Fountain, 2003).

Because extensive use is made of the three-decade long Landsat database, and data from other, more-recent multispectral sensors, it is imperative to know the accuracy of determining interannual glacier changes. Measurement errors are getting increasingly smaller as the satellite images are geocoded, and as the resolution of the images improves over time.

Glacier Ice-Velocity Determination

A highly efficient method for measuring terrain displacements consists of comparing multitemporal imagery. If the original imagery is used, the obtained displacements have to be rectified using the respective sensor model and orientation parameters (Kääb *et al*., 1997; Kääb and Funk, 1999). If ortho-images are used, the image comparison directly delivers the horizontal components of the surface-displacement vector.

The digital comparison between multi-temporal (ortho-) images may be accomplished by block matching techniques, or feature matching techniques. Block matching compares complete image sections to each other, feature matching compares geometric forms such as edges or polygons that are extracted from the imagery beforehand through pre-processing. Block matching techniques include two-dimensional cross-correlation, least-square matching or matching of interpolated Fourier functions (e.g., Scambos *et al*., 1992; Lefauconnier *et al*., 1994; Frezzotti *et al*., 1998; Kääb and Vollmer, 2000; Evans, 2004; Kaufmann and Ladstädter, 2003). Before the basic matching, it might be useful to apply filters to the raw imagery such as edge enhancements, interest operators, or global and regional radiometric adjustments.

Table 1 Errors derived in measuring glacier termini when using maps or satellite images (from Hall *et al*., 2003). ETM+ error does not refer to band 8 data.

Map or Image	Error
Map to Satellite	Unknown error
MSS to TM1	±136 m
TM2 to TM3	±5 m
TM4 to ETM+	±54 m
ETM+ to ETM+	±40 m
ASTER to ASTER	±21 m
4-m Ikonos to 4-m Ikonos	±5.7 m
1-m Ikonos to 1-m Ikonos	±1.4 m

Here, the horizontal displacements of individual terrain features are derived from multi-temporal digital ortho-images using the software Correlation Image Analyser, CIAS (Kääb and Vollmer, 2000). Measuring an individual horizontal displacement vector basically follows two steps (Figure 15):

1. In the orthophoto of time 1, an image section (so-called ‘*reference-block*’) with sufficient optical contrast is chosen. The ground coordinates of its central pixel are known from the orthophoto geo-reference.
2. The corresponding image section (so-called ‘test-block’) is searched for in a sub-area (so-called ‘test-area’) of the orthophoto of time 2. If successfully found, the differences in central pixel coordinates directly give the horizontal displacement between time 1 and 2 (Figures 16 & 17). The sizes of the *reference*- and *test-block* has to be chosen according to the textural characteristics of the ground surface. If the reference-block size is too small, the two-dimensional correlation function has no clear maximum; if the reference-block size is too large, computing time increases drastically. As a consequence of the ratio between typical sizes of terrain features, such as rocks and crevasses, and the spatial image resolution, we use small block sizes for satellite imagery (e.g., 7 × 7 pixels).

Matching blunders are detected and eliminated from analysis of correlation coefficients and from applying constraints such as expected ranges for flow speed and direction. In case of coherent displacement fields, additional spatial filters may be applied such as median or RMS thresholds. Glaciers usually show such a coherent velocity field due to the stress-transferring properties of ice.

In order to avoid distortions between the multi-temporal products, all imagery are adjusted as one image block connected by tie-points. For the multi-temporal model connection, these tiepoints are placed on stable terrain. From comparison with ground measurements and analytical photogrammetry, and from the noise within coherent flow fields, we found an accuracy of 0.5 to 1 pixel sizes of the applied imagery for the horizontal displacement measurements. It is important to note that the accuracy of such image matching is often restricted by terrain properties

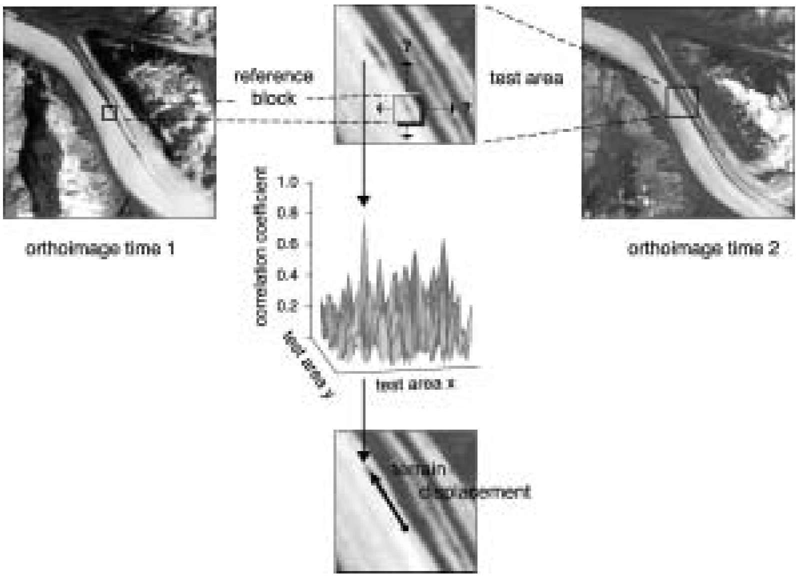

Figure 15 Principle of measuring horizontal terrain displacements from greyscale-matching between repeated orthoimagery. From Kääb and Vollmer (2000); Kääb (2002).

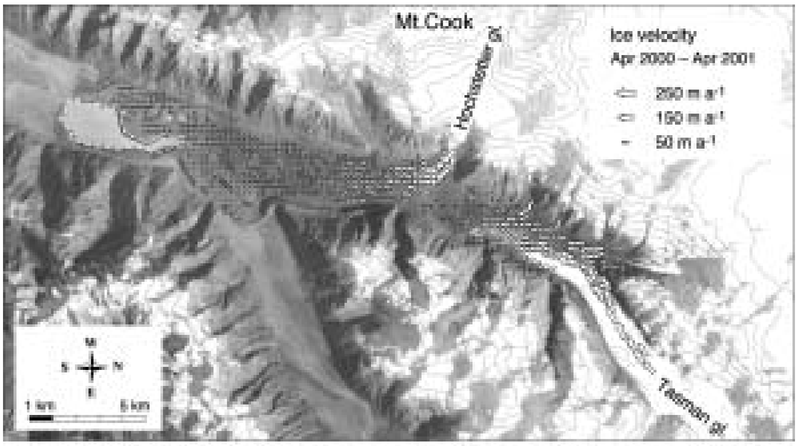

Figure 16 Ice flow vectors for Tasman glacier, New Zealand, (170º10' E, 43º35' S) as derived from ASTER images of 29 April 2000 and 7 April 2001. The original 100 m spacing of the raw measurements is re-sampled to 200 m spacing. Ice speeds amount up to 250 m a^{-1}. The marked- and surprising - decrease of ice flow for Tasman glacier at the confluence with Hochstetter glacier indicates a complex interaction between both glaciers. At the glacier terminus lake, a dashed line marks the lake extent of 7 April 2001 superimposed on the 29 April 2000m orthoimage. The observed lake growth towards the ice front amounts up to 130 m. From Kääb (2002).

and related changes with time, and not only by the precision of the applied algorithm.

Discussion

Remote sensing of the Earth's cryosphere has produced a tremendous volume of new spatial data that will provide a baseline from which to monitor changes in the cryosphere, providing new insights into ice-mass fluctuations and climate change. Glaciological field studies and preliminary GLIMS results indicate that small glaciers and glaciers from temperate and some high-latitude regions are downwasting and retreating (Dyurgerov and Meier, 1997; Arendt *et al*., 2002; Kääb *et al*., 2002). The GLIMS project will provide more quantitative information on the fundamental glaciological parameters, and permit initial assessments of the sensitivity of individual glaciers through change-detection studies.

It is tempting to generalize and extrapolate current findings, which are largely based upon small glaciers, to characterize the status of the Earth's cryosphere and project future trends. Details regarding regional ice-mass fluctuations and contributions to rising sea level, however, are difficult to estimate and know with certainty because:

1. Glaciers within a region can potentially exhibit negative and positive mass balance and exhibit different magnitudes of change, depending upon numerous controlling factors. We first need to be able to inventory existing conditions and be able to reliably produce quantitative estimates of glaciological parameters from space. Currently, the cumulative effect for many regions is unknown because the spatial and temporal variability in mass balance cannot be adequately assessed with current image-based, remote-sensing methods.
2. Radiative forcing is a major factor responsible for the ablation of ice. The topographic influence on the local energy budget for glaciers has not generally been taken into consideration in many areas. Topographic variations in mountain environments are highly variable, and this factor can produce significant local and regional variations in glacier sensitivity and their mass-balance gradients.
3. Atmospheric boundary-layer processes and landscape, hydrological-system components need to be accounted for. Increased evapotranspiration, surface runoff, and subsurface storage will alter the flux to the sea, given variations in geological and atmospheric conditions.
4. Finally, the variability in climate forcing is not known with certainty, and we can surely expect some surprises given changing solar, landscape, oceanic, and atmospheric conditions, which are coupled.

Perhaps the most difficult of these to account for is climate forcing. In the Himalaya, for example, we suspect a negative mass-balance trend based upon field data and other research (e.g., Cao, 1998; Aizen *et al*., 1997; Fujita *et al*., 1997; Bhutiyani, 1999; Meier *et al*., 2003). Monsoon forcing has been found to be associated with glacial advances in this region (Phillips *et al*., 2000; Shroder and Bishop, 2000). Monsoons are ultimately driven by the seasonal land-sea temperature contrast, which is induced by the different heat capacities of land and sea.

A wealth of proxy data indicate that the south Asian monsoon was once much stronger than it is today, both in terms of wind speed and precipitation (Prell, 1984; Street-Perrott and Harrison, 1985). Because wind speed impacts evaporation over the Arabian Sea, as well as inland penetration of the monsoon jet, the strength of the monsoon (both summer and winter) plays a crucial role in regulating Himalayan precipitation and snow accumulation (Benn and Owen, 1998; Richards *et al*., 2000).

Impacts of early-mid Holocene solar insolation on the monsoon have been studied in numerical simulations using general circulation models. Such experiments have confirmed the link between solar forcing and strength of the Asian monsoon (Kutzbach and Otto-Bliesner, 1982; Kutzbach and Guetter, 1984; Prell and Kutzbach, 1992). In addition, the connection between tropical sea surface temperatures and the strength of the monsoon has been shown to potentially dominate orbital forcing (Bush, 2001) and that, in the late Quaternary, a combination of these factors likely played a role in regulating the spatio-temporal extent of Himalayan snow accumulation (Bush, 2002).

Future snow accumulation and ice and sediment flux in the Himalaya will be severely impacted by increasing amounts of atmospheric carbon dioxide, but competing effects make it unclear which process – ice expansion or ablation – will dominate. Under a global warming scenario, it is important to note that, for the monsoon, it is the temperature gradient that is important, and not the actual values of temperature. For example, if temperatures were to increase uniformly everywhere, this would have little dynamical impact on the strength of the winds. It would, however, dramatically impact the hydrological component of the monsoon by increasing evaporation over the Arabian Sea and precipitation in the Himalaya. It could be the case that an increase in melting caused by warmer temperatures may be offset by an increase in snow accumulation caused by increased moisture flux into the Himalaya.

Climate simulations, coupled with remote sensing and GIS investigations, could provide us with new understandings of how glaciers in the Himalaya and elsewhere might respond to greenhouse-gas forcing. Simulations that account for higher temperatures produce an increase in the temperature gradient. Similarly, greater moisture flux into the Himalaya and precipitation could cause glaciers to exhibit positive mass balance. An increase in latent heat and glacier area could enhance the strength of the monsoon and produce more snow accumulation (Bush, 2000). This regional scenario is opposite to our current understanding of higher temperatures causing increased ablation and therefore glacial retreat.

To characterize the state of the Earth's ice mass distribution, remote sensing provides the only practical means to assess and monitor glaciers, by providing thematic and biophysical information at frequent intervals (Kieffer *et al*., 2000; Bishop *et al*., 2000). Furthermore, remote sensing and

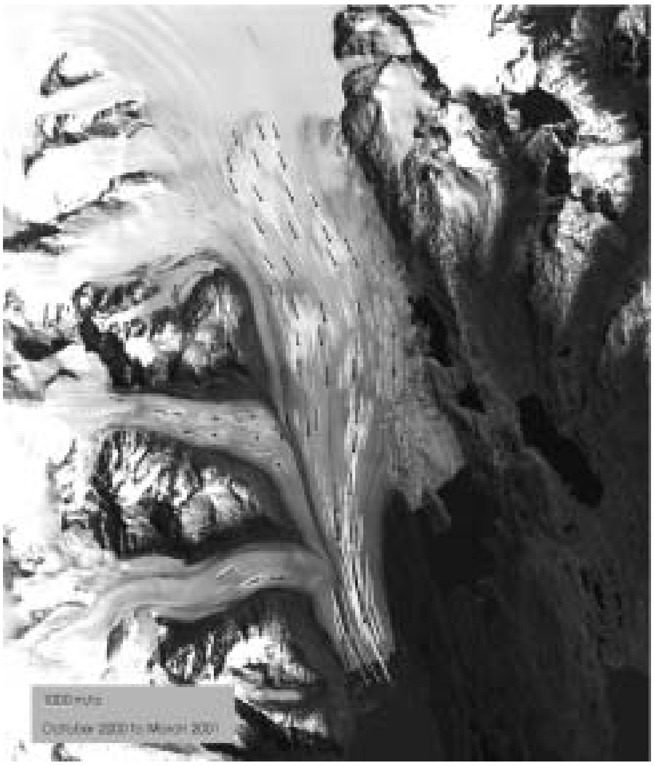

Figure 17 Landsat ETM+ image accquired 2001-1-14, showing Upsala Glacier, South Patagonia. All velocity vectors obtained from cross-correlation based, feature tracking between October 2000 to March 2001 are overlaid as white line segments, and a subset of these are overlaid as black arrows for clarity. Ice surface speed ranges up to just under 2000 m a^{-1}. The fast-moving calving front is approximately 2 km wide.

GIS investigations can play a critical role in studying climate forcing and glacier response (Bush *et al*., 2004). Scale-dependent (spatio-temporal) information extracted from satellite remote sensing and DEMs, coupled with detailed, field-calibration investigations, have the potential to greatly improve our ability to understand and monitor glacier process-structure and climate-glacier feedback relationships (Bishop *et al*., 1998a; Bush *et al*., 2004).

Multispectral analysis of debris-covered glaciers, which are characteristic of many regions of the world, still represents a problem that has not been thoroughly investigated (Bishop *et al*., 1995, 1998a, 1999, 2001). Quantitative remote-sensing studies are needed to examine and characterize supraglacial characteristics. Consequently, a comprehensive approach to information extraction and glaciological characterization of glaciers from space is sorely needed.

In complex environments, information extraction from satellite imagery is complicated by the relatively low-to-high frequency, spatial-reflectance variations caused by the atmosphere, topography and biophysical variations of matter on the landscape. Numerous investigators have developed and tested algorithms for normalizing reflectance variations related to the atmosphere and topography (e.g., Dozier and Frew, 1981; Colby, 1991; Vermote *et al*., 1997; Bishop *et al*., 1998b; Bishop and Colby, 2002), so that radiometrically calibrated data can be used to produce more accurate thematic and biophysical information. Many other investigators have found, however, that anisotropic-reflectance correction and calibration issues are not the only problems that must be addressed for extracting reliable information, as spectral, spatial and topographic information (i.e., spectral features, spatial features, geomorphometric parameters), are essential for quantification and mapping of complex patterns in these environments (Allen and Walsh, 1996; Gong, 1996; Bishop *et al*., 1998a,b, 1999; Kääb *et al*., 2002). Despite these advances in using additional information, results are dependent upon the complexity of the terrain, data quality and measurement scale, ability to integrate multi-source data, spatial-analysis approaches, and pattern-recognition algorithms. Furthermore, increased spectral-reflectance variability from high-resolution imagery has been found to cause problems, as traditional classification methods have numerous limitations (Gong, 1996). This has been empirically demonstrated by Franklin and Wilson (1992), where they developed and tested a new three-stage classifier to overcome extreme spectral variability in a complex environment.

Attempting to assess and map glaciers via ASTER and ETM+ data using traditional approaches will permit the production of baseline information that allows change-detection studies. The use of various techniques and brute-force classification algorithms, however, do not produce consistently high-quality results (Bishop *et al*., 1999), and quality information production often requires significant pre-analysis steps and a priori knowledge of the study area. Consequently, the GLIMS consortium is developing new approaches to address classification and assessment problems, as new technologies and approaches have considerable potential for information extraction from remotely sensed data and spatial data in GIS data bases.

Given the various uncertainties associated with spatial data and standard, information-extraction approaches/algorithms, caution is warranted in terms of interpreting remote sensing results. Although the advantages of remote sensing and GIS investigations are widely recognized, numerous issues need to be addressed, and these require the sophisticated use of remote sensing science and geographic information technology. More research into the following topics is necessary to reduce the level of uncertainty associated with assessing the Earth's glaciers from space:

- Topographic solar-radiation transfer (TSRT) modeling. Improved mapping of glaciers and change detection using satellite multispectral imagery will require operational ARC to radiometrically calibrate imagery and reduce the atmospheric and topographic effects. Accounting for multi-scale topographic effects in modeling the irradiant and radiant flux should permit effective "topographic normalization" based on our preliminary modeling results. Accurate DEM generation capabilities are essential in this effort.
- Landscape BRDF modeling. Field BRDF measurements of supraglacial facies are required to validate BRDF modeling results. Furthermore, it is necessary to establish the nature of the relationship between reflectance anistropy and surface properties, solar geometry, viewing geometry, and wavelength dependence. This is essential for TSRT modeling to accurately estimate the surface irradiance, and in making use of an asymmetry parameter (e.g., Hapke, 1981) that will enable investigation of using reflectance anistropy for glacier mapping and delineation of supraglacial facies.
- Integration of topographic information. Debris-covered glaciers are difficult to map using spectral data alone. Research indicates that mapping results can be significantly improved by using topographic information in manual or computer-assisted approaches. Per-point analysis of spectral and topographic data, however, is generally not very effective for mapping debris-covered glaciers due to scale-dependent supraglacial features and highly variable glacier topography. Consequently, new approaches to GIS-based data modeling and spatial analysis, which address the issue of scale and topology, need to be further investigated, as our preliminary results indicate that this approach may significantly improve glacier mapping and permit semi-automated analysis (Bishop *et al*., 2001; Paul *et al*., 2004).
- Scientific visualization. Visualization of spatial data sets has progressed significantly over the years, such that 3-D perspectives of satellite images are now routine. Greater interactivity and control of visualizing imagery, analysis and classification results are warranted, so that Earth scientists can better assess the accuracy of results in context with other characteristics of the landscape.
- GIS-based physical models. GIS-based physical models that utilize information from imagery and databases are required to better estimate glaciological parameters. For example, the integration of a TSRT model with surface energy-budget modeling and spatial data can be used to estimate ablation rates, the mass-balance gradient and the equilibrium line altitude (ELA). This type of modeling is sorely needed as the influence of the topography on radiative forcing is not always accounted for, and the glacier distribution and debris-cover spatial variation and depth can be mapped and estimated using satellite imagery and field data. This approach might also be useful for estimating the sensitivity of glaciers to climate forcing, as the mass-balance gradient and glacial topography are strongly related to changing atmospheric and flow conditions (Dyurgerov and Dwyer, 2000).

These and other aspects of GLIMS research should improve the quality of information about the Earth's ice masses and establish a foundation for automated analysis in the future. This will be accomplished by multidisciplinary research involving Earth scientists and information scientists. Technically, progress is being made through the integration of spectral analysis, spatial analysis, geomorphometric analysis and physical modeling. This type of research is required to accurately assess the Earth's cryosphere and reduce the uncertainties associated with improving our understanding of climate forcing and glaciation, and predicting the impact of global warming on the human and natural dimensions of environmental change.

Conclusions

The international Global Land Ice Measurements From Space project is a USGS-led consortium of more than forty universities and research institutes, whose purpose is to assess and monitor the Earth's glaciers. Remote sensing and GIS technology play an important role in assessing complex and remote environments as well as in the quantitative analysis and modeling of radiation transfer, surface energy budgets, glacier ablation and mass-balance estimates and climate simulations. To date, preliminary remote sensing and GIS investigations coupled with field data indicate that small glaciers and glaciers in temperate regions are generally downwasting and retreating, although detailed information regarding glacier mass-balance gradients and regional trends has yet to be determined from space. These and ongoing studies have identified numerous issues associated with accurate mapping and assessment of glaciers from space. GLIMS-related research will address these issues and develop and implement new approaches to information extraction from spatial data. Our findings indicate the need to establish an integration of field studies with remote sensing and GIS investigations, and develop new GIS-based physical models that make use of satellite imagery and DEMS to account for spatial variation of phenomena and serve as constraints in modeling efforts. Such remote sensing/GIS studies are vital for producing baseline information on glacier changes, and improving our understanding of the complex linkages between atmospheric, lithospheric, and glaciological processes.

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