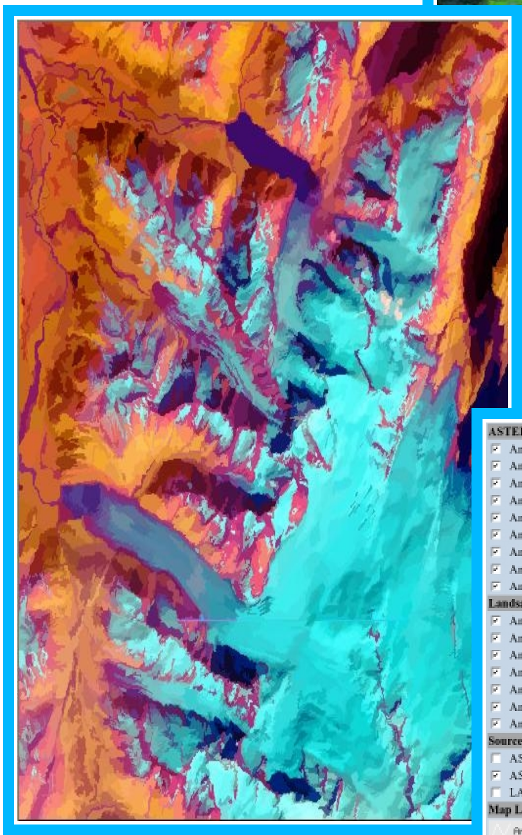
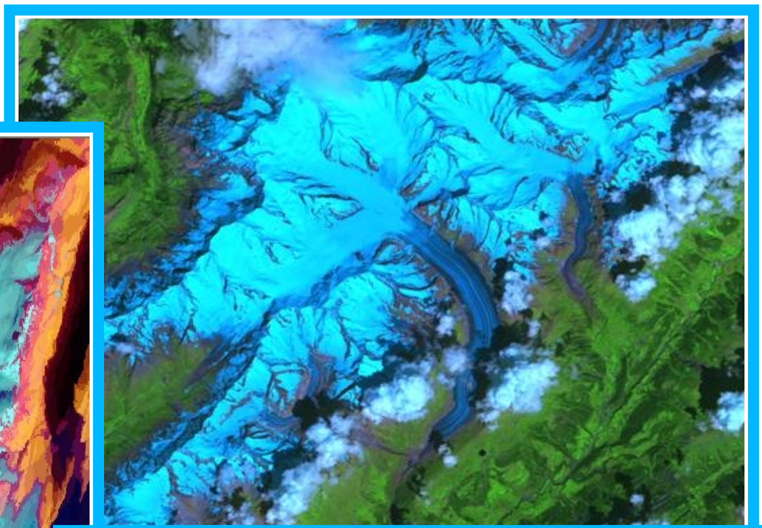
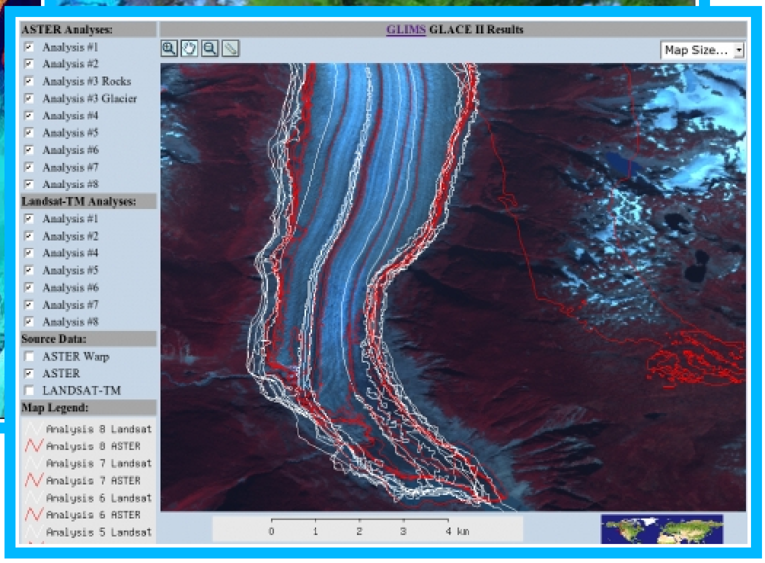
Global Land Ice Measurements from Space (GLIMS)

Workshop 2006







Program and Abstracts

Scott Polar Research Institute, Cambridge, England

17 – 18 August 2006

We would like to welcome you to the GLIMS Cambridge Workshop 2006

Global Land Ice Measurements from Space (GLIMS) uses remote sensing methods and supporting field studies to undertake a global glacier assessment. It aims to provide a coherent framework to undertake objective measurements of the current and recent state and dynamics of the world's glaciers and to provide public access to these data.

GLIMS welcomes you to the historic university town of Cambridge (UK). This two-day workshop includes representatives from 13 countries working on a variety of GLIMS-related research areas. It is through discussion and hands-on learning that we hope to further research into the distribution and characteristics of glaciers worldwide, so as to better understand glacial processes and predict how these ice masses may respond to future climate scenarios.

We look forward to a productive and stimulating workshop.

Please enjoy your time in Cambridge.

-- **Jeff Kargel (University of Arizona)**

Images on Front Cover:

- **Top Right:** This ASTER image, acquired on July 23, 2001, shows Aletsch Glacier, the largest glacier of Europe. (Image by Earth Observatory Team, based on data provided by the ASTER Science Team). Taken from: Yohe, E., 2004. Sizing up the Earth's glaciers. Available: http://earthobservatory.nasa.gov/Study/GLIMS/

- **Centre Left:** A 4, 3, 2 (ASTER) color composite, Histogram stretch of the GLIMS glacier that is being used in this project. The Mid-IR band (4) is being fired through the red gun, the Near-IR band (3) is being fired through the green gun, and the Red band (2) is being fired through the blue gun. Taken from: Fyvie, J., 2004. Object-Oriented Image Analysis. Available: http://www.gis.unbc.ca/courses/geog499/projects/2004/jayf_glims_web/index.htm

- **Bottom Right:** Results of the GLACE (GLims Analysis Comparison Experiment) 2, showing the need for (1) well defined glacier classification protocols, and (2) use of elevation data in the analysis. Taken from: Raup B. et al. 2006. GLIMS test of variability in glacier analysis from satellite imagery. Available: http://instaar.colorado.edu/AW/abstract_detail.php?abstract_id=71

This Workshop would not have been possible without the following sponsors:

GLIMS-University of Arizona/Tucson

NASA: ASTER Science Team project support for Jeff Kargel

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Special thanks to the International Glaciological Society (IGS) and British Antarctic Survey for website and organisational support in collaboration with the IGS *International Symposium on Cryospheric Indicators of Global Climate Change*.

We also extend thanks to all the individuals that put their time and energy into making this workshop successful.

PROGRAM

GLOBAL LAND ICE MEASUREMENT FROM SPACE (GLIMS) WORKSHOP 2006

PROGRAM

Underline indicates speaker/presenter/discussion leader

Thursday August 17, 2006

Jeff Kargel, chairperson

9:00 - 9:45 Registration

9:45 - 10:00 Official welcome

Topic 1 GLIMS: Coordinating Global Observations

10:00 - 10:40 **Perspectives for Glacier Monitoring in Global Climate-related Observing Systems**
Wilfried Haeberli

10:40 - 11:00 **ESA's GlobGlacier project**
Espen Volden

11:00 - 11:30 *Break with refreshments*

11:30 - 11:50 **The Western Canadian Cryospheric Network (WC2N): monitoring present and former glacier extents and volume changes**
Roger Wheate and Brian Menounos

11:50 - 12:10 **The contribution of the Global Land Ice Measurements from Space (GLIMS) program to mapping changes in glacier area and volume in the Queen Elizabeth Islands, Canada**
Fiona Cawkwell

12:10 - 1:20 *Lunch*

1:20 - 1:40 **An Automated Method to Delineate the Debris-Covered Glaciers at Mt. Everest Based on ASTER Data**
Tobias Bolch, Manfred Buchroithner and Ulrich Kamp

1:40 - 2:00 **Tracing the *lines* of Icelandic glaciers: outline, equilibrium line, and firn line**
Oddur Sigurðsson

Topic 2 Digital Elevation Models

2:00 - 2:20 **Extraction and Evaluation of DEM Derived from the ASTER Stereo Data**
Qiang Shen

2:20 - 2:40 **Digital elevation models from ASTER along-track stereo. Performance, limitations and workarounds**
Andreas Kääb

2:40 - 3:00 **DEMs from ASTER Imagery – A Comparison of Available Tools and Implications for GLIMS**
Siri Jodha Singh Khalsa

3:00 - 3:30 *Break with refreshments*

Afternoon Poster Session

3:30 - 3:32 **Glacier Retreat during the last 50 Years in Northern Tien Shan (Kazakhstan/Kyrgyzstan) using Remote Sensing Data**
Tobias Bolch

3:32 - 3:34 **Recent Changes in Glacier Extent (1985-2000), Caucasus Mountains, Russia**
Chris Stokes, S. Gurney, M. Shahgedanova and V. Popovnin

3:34 - 3:36 **A glacier inventory for the Buordakh Massif, Cherskiy range, north east Siberia, and evidence for recent glacier recession**
S. Gurney, V. Popovnin, M. Shahgedanova and Chris Stokes

3:36 - 3:38 **Solid Ice fluxes From The Greenland Ice Sheet**
Mohamed Babiker, Martin Miles, Stein Sandven

3:38 - 3:40 **Statistics on GLIMS ASTER Acquisitions over GLIMS Study Areas**
Christopher Helm, Bruce Raup, Siri Jodha Singh Khalsa, Richard Armstrong

3:40 - 3:42 **How accurately can we map tropical glaciers using satellite remote sensing?**
Andrew Klein, Joni Kincaid and Kevin Merritt

3:42 - 5:00 Poster discussion time

5:00 *Adjourn sessions*

Friday August 18, 2006

Bruce Raup, Chair person

Topic 3 Glacial Lakes

9:00 - 9:20 **ASTER Investigations of Glacier Lakes: Occurrence, Metastable Growth and Dynamics, Transient Behaviors and the Future**
Jeffrey Kargel

9:20 - 9:40 **Methods for Modeling Photon Transport in Ice and Water Media: Theory and Numerical Implementation**
Roberto Furfaro and Jeffrey Kargel

9:40 - 10:00 **Remote Sensing Analysis of Glacial Lake Colors via Model-Based Intelligent Algorithms: Coupling Radiative Transfer and Neural Networks to Estimate Flour Concentration in Glacial Waters**
Roberto Furfaro

10:00 - 11:30 *Break with refreshments*

11:30 - 1:30 **GLIMSView Session** (Geography Building)
Bruce Raup

1:30 - 2:30 *Lunch*

Topic 4 Glacier Inventories: Progress and Problems

2:30 - 2:50 **GLIMS: database status**
Bruce Raup, SJS. Khalsa, R. Armstrong and C. Helm

2:50 - 3:10 **A new remote-sensing-derived glacier inventory for Norway - first results**
Liss M Andreassen

3:10 - 3:30 **The pilot study of glacier changes in West China using RS data and Chinese Glacier Inventory**
Shangguan Donghui

3:30 - 4:00 *Break with refreshments*

4:00 - 4:20 **Problems related to the creation of a glacier inventory: Can we find consistent solutions?**
Frank Paul

4:20 - 4:40 **The GLACE image comparison experiments**
Bruce Raup

4:40 - 5:00 Discussion on glacier definition and delineation

5:00 *Close of workshop*

8:00 - 11:00 **Workshop dinner – Riverside Restaurant**
University Centre, Granta Place, Mill Lane, Cambridge
Speaker – Andreas Kääb on **'Glacier hazards and other threats'**

Abstracts

GLOBAL LAND ICE MEASUREMENT FROM SPACE (GLIMS) WORKSHOP 2006

Order: alphabetically by surname of first author
See list of participants at end of program for full listing

ABSTRACTS

Order: alphabetically by surname of first author

ABSTRACT 1

A new remote-sensing-derived glacier inventory for Norway - first results

Liss M Andreassen

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Glaciers cover about one percent of the land area in mainland Norway. Long term monitoring of Norwegian glaciers includes mass balance, length change and survey. Although the Norwegian glacier data set is comprehensive, most glaciers are unmeasured. A detailed survey of the total glaciated area in Norway have not been performed since the glacier inventories were compiled in the mid 1980s for southern Norway and start of the 1970s for northern Norway. Thus, a new updated survey of the Norwegian ice masses is required in order to get an overview of the present state of the glaciers and the changes of them. As a GLIMS regional centre for Norway, NVE has in 2006 started work in order to compile a new satellite based inventory of mainland Norway. The strategies and the first results from analyses of satellite imagery will be presented at the workshop.

ABSTRACT 2

Solid Ice fluxes From The Greenland Ice Sheet

Mohamed Babiker, Martin Miles, Stein Sandven

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The mass loss from the Greenland Ice sheet composes of melt-water and solid ice. The outlet glaciers of Greenland can drain large volumes of solid ice, via calving of iceberg and bottom melting from floating ice tongues. The contribution of these solid-ice fluxes is controlled by ice dynamics, such that it had been generally believed to have a relatively slow response to climate forcing or changes in boundary conditions. However, this assumption has recently been questioned and observations of one surging glaciers in northern Greenland suggest relatively large and rapid changes in flux are possible. The magnitude of solid ice entering the ocean from the Greenland Ice Sheet can be determined by deriving the ice flux crossing line of calving glaciers, using remote sensing data and ancillary data. The main objective is to identify the spatial-temporal variability and possible trends in calving fluxes for the major glaciers in northern Greenland, which are relatively unknown. The methodology approach will be observational, based primarily on analysis of repetitive satellite data over a period starting from 1990.

ABSTRACT 3

Glacier Retreat during the last 50 Years in Northern Tien Shan (Kazakhstan/Kyrgyzstan) using Remote Sensing Data

Tobias Bolch

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Email: tobias.bolch@tu-dresden.de

The glaciers of the mountain ridges Zailiyskiy and Kungey Alatau, which represent an important part of the Northern Tien Shan, are retreating like in many other parts in the world. In order to quantify the aerial retreat first the recent glacier coverage was delineated in a semi-automated way using a TM4/TM5 ratio image of a Landsat ETM scene from the year 1999 and a merged ASTER/SRTM3-DEM. Then the extent of these glaciers was compared with those of the Soviet Glacier Inventory, which represents the situation in study area in approx. 1955, with glacier areas of the late 1970s digitized from topographic maps and a Landsat MSS scene and with those of 1990 based on the Kazakh glacier inventory and a Landsat TM scene. Regionalization of temperature and precipitation based on 16 gauging stations situated in different altitudes as well as solar radiation calculation were conducted in order to determine the climate situation at the glaciers.

On the average, the decrease in ice extent was more than 32% between 1955 and 1999 in the investigated valleys of Zailiyskiy and Kungey Alatau. The retreat clearly became pronounced in the 1970s and has decreased slightly since about 1990. However, the glacier retreat was not homogeneous, but depended strongly on the size, location and climate regime at the glaciers. The area loss of the continental-type glaciers with very predominant summer accumulation, as for those situated in the deeply incised Chon-Kemin valley between Zailiyskiy and Kungey Alatau, was conspicuously less (20%), in parts, than the loss at the more maritime glaciers on the northern slope of Zailiyskiy Alatau (~35%). This is consistent with the small increase in summer temperatures. However, under dryer conditions with high solar radiation input, such as with glaciers in the Chon-Aksu valley in Kungey Alatau, the area retreat of the continental-type glaciers can be even more pronounced than that of the more maritime glaciers (~40%).

ABSTRACT 4

An Automated Method to Delineate the Debris-Covered Glaciers at Mt. Everest Based on ASTER Data

Tobias Bolch, Manfred F. Buchroithner and Ulrich Kamp

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Large areas of the glacier tongues at Mt. Everest are heavily covered by debris. Recent glacier shrinkage results even in an increasing coverage. This hampers the mapping of the actual ice snout by means of spaceborne imagery. On the other hand, satellite imagery would represent an ideal tool to develop an automated way of outlining the glacier ice extents. Using ASTER stereo images of the Mt. Everest test area, a team of the TU Dresden Institute for Cartography undertook the task to solve this problem. Combining ASTER´s thermal information with various shape parameters derived from stereo models, both the actual glacier beds and the marginal moraines along the active glacier, could be obtained. The results are quite promising. Field verification in the Mt. Everest Area in spring 2006 very well showed the proof of concept.

ABSTRACT 5

The contribution of the Global Land Ice Measurements from Space (GLIMS) program to mapping changes in glacier area and volume in the Queen Elizabeth Islands, Canada

Fiona Cawkwell

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Researchers from the University of Alberta have overseen the construction of the Canadian Arctic database, with the acquisition of Landsat and ASTER imagery and the development of automated techniques of ice margin discrimination. Currently many of these data are being reconfigured to be in a format compatible with the web-based NSIDC interface.

In addition to determining ice extents at the start of the 21st century, the Alberta group have also been able to extract information on changes in ice area and volume as compared to ice margins at the time of a comprehensive aerial photographic survey in 1959/60. The Queen Elizabeth Islands of the Canadian Arctic represent the largest ice covered area outside of the Greenland and Antarctic ice sheets, with seven major ice caps and many smaller glaciers and icefields. Between 1960 and 2000 glacier shrinkage occurred throughout much of this region, with a total loss of 3023km^2, or 2.8% of the 1959/60 ice area. Most outlet glaciers retreated over this period, although a small number advanced (notably on Axel Heiberg Island due to glacier surging). The estimated ice volume loss is 718km^3, equivalent to an increase in sea level of 1.79mm. Although the larger ice caps contributed most to the net loss in ice area, the proportion of ice lost as a function of area was greatest for the smaller ice masses. The net reduction in area of these small ice masses (965 km^2) represents 34% of the total ice area loss in this region, although they constitute only 5% of the ice covered area. The more southerly regions showed a greater areal loss of these small ice masses, however the development of multiple linear regression models reveals that latitude is not the only control on ice loss. Other factors of significance include ice area, geometry, topography and equilibrium line altitude, however regional variations indicate the complexity of inter-relationships between glaciated areas and environmental changes.

ABSTRACT 6

The pilot study of glacier changes in West China using RS data and Chinese Glacier Inventory

Shangguan Donghui

Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, China
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Changes in extent of the mountain glaciers are important facts for understanding past climates. In present work, glaciers in northwestern China have been monitored by applying the Chinese Glacier Inventory (CGI), Landsat Enhance Thematic Mapper (ETM+) and ASTER images from 1999-2001, all of which have been compared in order to detect areal changes through the past four decades. The first Chinese Glacier Inventory (CGI) saved by paper map was converted into digital format as GIS (geographic information system)-based vector files for further processing. For mapping the glacier distribution in 1999-2001, some automatic methods such as the threshold of a ratio image from TM4/TM5 from DN, NDSI, Supervised and unsupervised classification were used to obtain glaciers boundary for the research region. However, most of glaciers are mapped by manually delineation with view interpretation, and especially debris-covered glaciers need combine with DEM. These data are projected in an Universal Transverse Mercator (UTM) coordinate system referenced to the World Geodetic System of 1984 (WGS84).

In Tarim basin, we obtained area change of about 7665 alpine glaciers among 11665 glaciers. The results show that the 3.3% area reduction as observed for the period CGI to 1999/2001 and glaciers with area within 1-5km^2 contribute 48.3% to the total loss. However, the glacier changes in the past decades showed regional characteristic and glaciers retreat about -0.7%--7.9% in each sub-basin of Tarim. In addition, two surging glaciers were also found in Yarkant River.

In Tibetan Plateau (TP), we select different type glaciers in southeast TP, Center TP and North TP. The results show that the glacier changes in Nyainqen Tanglha (sub-continental) decreased about 5.7% while the glacier changes in southeast TP(Maritime type) and north TP (extreme-continental) decreased slightly (less than 2%), and even glaciers change in Malan Ice Cap enlarged about 1.2%. Comparison of all research of glacier change in TP, we found that the changes of sub-continental glaciers are the largest than Maritime type and extreme-continental type glacier in TP. Moreover, the glacier shrinkage of sub-continental glaciers in center of TP is the least than south TP (such as pengqu basin) and east TP (For example, A’nyêmagên Mountain).

ABSTRACT 7

Remote Sensing Analysis of Glacial Lake Colors via Model-Based Intelligent Algorithms: Coupling Radiative Transfer and Neural Networks to Estimate Flour Concentration in Glacial Waters

Roberto Furfaro

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Over the past few years, glacial lakes and streams have been the subject of extensive investigation due to the key influence exerted on global glacial dynamics and mass balance. On a more practical basis, they represent the boundary connection between humans and glaciers. Remote sensing platforms collect, on a routinely basis, multispectral data (e.g. ASTER, MODIS) that can be used to map and characterize glacier lakes and streams. While conventional classification schemes can be applied to perform the mapping task, physical inside and understanding of the structure of such objects can be obtained by basic application of radiative transfer principles. For example, the famous turquoise color of glacial lakes can be linked to meltwater deposits and sedimentation processes where light scattering and absorption play a dominant role.

To quantify such effects and construct algorithms that employ multi/hyperspectral data to retrieve the amount of concentration of suspended matter in glacier lakes and streams, we used first principles to model the interaction between light and water-made structures. Balance of photons leads to the definition of the steady-state, one-dimensional radiative transfer equation (linearized Boltzmann equation [1]) which describes the radiative regime within and top-of-glacial lakes and streams. The characterization of the scattering and absorption coefficient as function of the wavelength and concentration of suspended matter and plankton has been derived from case-2 lake waters [2]. The radiative transfer equation is conventionally used in forward mode, i.e. given the optical properties of the lake/stream under consideration, the hemispherical spectral reflectance is computed to simulate the sensor response. Naturally, the inverse problem is the most interesting in practical remote sensing (i.e. given the sensor data, characterize the optical properties of the observed surface).

Neural network algorithms can be effectively used to solve inverse problem in remote sensing [3] and can be a valuable tool in a) monitor changes in particle concentration b) link the particle concentration with the change of glacier lake/stream colors c) help the mapping of such complex environments. A neural "intelligent" network algorithm based on the radiative transfer equation has been devised. A 12-20-2 multilayer network has been designed and trained using the levenberg-marquard optimization scheme to learn the inverse relationship between spectral reflectance collected by the sensors and concentration of glacial flour and plankton. The network is shown to be accurate with maximum 0.2% relative error when training with no noise. Sensitivity analysis is performed to understand the effect of modeling and measurement uncertainties. The analysis shows the potential of the methodology when applied to the analysis of glacial lakes and streams.

References

[1] Ganapol, B. D., Furfaro R., (2006) "A Converged Discrete Ordinates Method for Radiative Transfer in Plane-Parallel Media" to be submitted to JQSRT

[2] Albert, A., Mobley, C.D., (2003), "An analytical model for subsurface irradiance and remote sensing reflectance in deep and shallow case-2 waters", 3 November 2003 / Vol. 11, No. 22 / OPTICS EXPRESS 2873

[3] Kimes, D. S., Nelson, R. F., "Attributes of neural networks for extracting continuous variables from optical and radar measurements", int. j. remote sensing, 1998, vol.19, no. 14, 2639- 2663.

ABSTRACT 8

Methods for Modeling Photon Transport in Ice and Water Media: Theory and Numerical Implementation

Roberto Furfaro[a] and Jeffrey S. Kargel[b]

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Remote sensing of Earth regions containing ice and surface water (e.g. glaciers, glacier lakes and streams) is important to understand the effects of dynamical changes occurring in such areas. Radiative transfer theory can be an effective tool to help the interpretation of the remote sensing signal collected by satellite sensors (e.g. ASTER, MODIS) as well as to help the spectral characterization of the areas under observation. Moreover, the theory can help scientists use spectral data to constrain conceptual models of glaciers, analytical and numerical process models, and forecasts of future behavior and impacts of changing glaciers on regional hydrology. The interaction between light and ice/water media can be understood using first principles describing the physics of photon transport in participating media.

In this talk we will show how the basic conservation of particles (photons) is applied to derive the linear Boltzmann equation, which represents the generic model employed to describe the physics of particle-medium interaction. The characterization of the participating medium takes place via knowledge of its optical properties defined to describe the scattering and absorption mechanisms. We will briefly discuss (1) numerical techniques employed to determine the remotely-sensed reflectance factor; (2) the glaciological basis for improvement in numerical techniques for analysis of multispecral data. Various scenarios (e.g. pure ice, pure water, mixture of ice and water, patches of ice and rock debris, and ice containing fine dust) will be presented and analyzed in the light of radiative transfer theory to determine the most appropriate strategy for modeling such complex media.

ABSTRACT 9

A glacier inventory for the Buordakh Massif, Cherskiy range, north east Siberia, and evidence for recent glacier recession

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In recent years, it has been well documented that mountain glaciers are undergoing widespread retreat, with potentially serious implications for the environment. Before a global picture can be compiled, however, there are a number of regions which must first be documented. Such a region is the remote Buordakh Massif, in the Cherskiy Range of north east Siberia which contains mountains of over 3000 m and despite its arid, continental climate, numerous glaciers. This paper presents the only georeferenced glacier inventory for the region, containing some 80 glaciers, which range in size from 0.1 to 10.4 km^2 (total glacierized area is ca. 70 km^2). The mapping is based on Landsat 7 ETM+ satellite imagery from August 2001, augmented by field investigation at that time. These glaciers are of the 'firn-less', cold, continental type whose mass balance relies heavily on the formation of superimposed ice. The most recent glacier maxima are also mapped (believed to date from the Little Ice Age ca. 1350-1850 AD). Glacier areal extent has reduced by some 14.8 km^2 since this most recent maximum. Further and possibly accelerated retreat might be expected since local climate records indicate that summer air temperatures have been steadily increasing since the 1980s.

ABSTRACT 10

Perspectives for Glacier Monitoring in Global Climate-related Observing Systems

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Internationally coordinated observation of glacier fluctuations started in the late 19th century. The history of this long-term environmental monitoring program is a reflection of excellent worldwide collaboration but has also seen repeated crises. During the past two decades, however, glaciers have been increasingly recognised as key indicators of global climate change. Corresponding quantitative information now regularly forms part of international assessments (IPCC, GCOS, UNEP reports). This increasing significance together with important future challenges and possibilities brought in by new technologies (remote sensing, geo-informatics) make it a most urgent necessity to reorganise global glacier monitoring. To this purpose, an advanced integrative/multilevel strategy has been developed, which – by using numerical modelling to tie together the individual components – allows for a combination of in-situ with remote observations, traditional with new techniques and process understanding with global coverage. In addition, reconstructions of former glacier geometries – to extend the existing fluctuation series back in time – are to be integrated. The Global Terrestrial Network for Glaciers (GTN-G) within GTOS/GCOS aims at combining corresponding efforts presently undertaken by the World Glacier Monitoring Service (WGMS; primarily „in-situ“ measurements: mass balance, length change) and the Global Land Ice Measurement from Space-project (GLIMS; satellite imagery, digital terrain information).

Possible future climate-driven scenarios of rapid decay, disintegration and even complete disappearance of glaciers in many mountain ranges – including the possible loss of glaciers with long mass-balance series within a few decades – call for an adequate monitoring program for the 21st century including advanced technologies and data bases for reaching global coverage, automated data retrieval and analysis, extrapolation of obtained results in space and time, assessment of impacts, etc. A corresponding organizational structure as part of the global climate-related observing systems (GTOS/GCOS, GEOSS) must comprise an enlarged but effective and truly international lead team with an adequate share of national and international funding. The lead team should involve experts responsible for the three main components: in-situ measurements, remote observations and numerical models. Close collaboration with the WDC Glaciology and its capacity for data management and dissemination is fundamentally important.

ABSTRACT 11

Digital elevation models from ASTER along-track stereo. Performance, limitations and workarounds

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Digital elevation models (DEMs) are a crucial prerequisite for satellite-derived glacier mapping and monitoring. DEMs are, for instance, needed for orthorectification of satellite images, derivation of three-dimensional glaciological parameters, or detection of firn divides. The ASTER instrument carries an along-track stereo-sensor in addition to the multispectral nadir-looking sensors. This setup allows for simultaneous multispectral and three-dimensional analyses, which greatly support glaciological investigations from space.

In this contribution we present a number of test studies in order to estimate the accuracy and other characteristics of ASTER DEMs under different terrain and image conditions. We also give a systematic overview about the principle limitations of optical satellite stereo in general, and ASTER DEMs in particular. A number of workarounds are proposed in order to improve ASTER DEMs. Particular focus will be on comparison and combination of ASTER DEMs with the SRTM DEM. Finally we present some glaciological applications of ASTER DEMs and discuss the propagation of DEM errors in the derived products.

ABSTRACT 12

ASTER Investigations of Glacier Lakes: Occurrence, Metastable Growth and Dynamics, Transient Behaviors, and the Future

Jeffrey S. Kargel

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Lakes are integral parts of many glaciers and commonly are formed by glaciers during their advance and retreat phases and when they are in steady state. Different types of lakes tend to form during these different phases. The types of lakes formed and lake dynamics depend on glacier dynamics and recent history; the size of the glacier; its relation to bed topography, adjacent topography, glacier surface relief and hypsometry; the lithology of erosional debris; the geophysical, climatic, and hydraulic environment of the glacier and lake. The hazards they present depend on human population and infrastructural development downstream from the lake. In general these lakes are dynamic and are either unstable or metastable. Their metastability depends on (1) the primary material damming the lake and its propensity to disintegrate, melt, or be buoyed up (cold ice, melting ice, rock debris, and bedrock each have different responses); (2) surges in water input rate to the lake from sources such as melting of runoff from the glacier, rainfall runoff from the glacier and adjoining rock surfaces, and subglacial water inflow; and (3) sudden high-momentum discharges of ice, water, or rock debris into the lake from other sources.

Types of glacier lakes, regardless of size and hazards significance, are listed here according to formation and damming mechanism: (1) supraglacial lakes; (2) glacier-marginal lakes formed at the side of a glacier and contained on the other side by bedrock; (3) moraine-dammed lakes formed in contact with ice on one side and contained on the other side by rock debris of a moraine; (4) glacier-dammed river, with damming by either advancing glaciers (especially surging glaciers) or by ice and moraine avalanches and glacier-issued debris flows. Glacier lakes may involve either polar ice or subfreezing permafrost; or temperate melting ice. The drainage dynamics of these lakes differs greatly. With climate changing and glaciers responding, the occurrence and type of glacier lakes and their dynamics is also changing.

ASTER images of these various types of lakes will be used to illustrate lake occurrence and to characterize the dynamics of glacier/lake systems. Although ASTER lacks the temporal repeat imaging needed for full monitoring capability, it has the other attributes of an effective monitoring system that can track lake turbidity, iceberg cover, surface water temperature, and size. Climate change trends and patterns and modeled projections of future climate changes will be used to highlight expected patterns of future lake occurrence and expected future shifts of the patterns of transient dynamical events. This conceptual model will then be used to outline an observational multi-instrument program to support glacier lake monitoring.

ABSTRACT 13

DEMs from ASTER Imagery – A Comparison of Available Tools and Implications for GLIMS

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This paper will discuss options for producing digital elevation models (DEMs) from ASTER imagery. Sample scenes from different glacierized regions of the world are used to compare the performance of the Silcast, PCI Orthoengine and RSI ENVI software modules. DEMs produced from the ASTER scene used in the GLACE-2, containing the Klinaklini Glacier, are compared with the Canadian National Digital Elevation Dataset and SRTM. We examine the strengths and weaknesses of each software package and attempt to discern the conditions under which each performs best.

ABSTRACT 14

Statistics on GLIMS ASTER Acquisitions over GLIMS Study Areas

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The GLIMS Glacier Database now contains records on all ASTER L1A scenes acquired over regions known to contain glaciers. We present the details of the GLIMS-designed tools for accessing the Terra ASTER Metadata Inventory (TAMI), the selection of GLIMS relevant images, and the acquisition of associated browse imagery. The ASTER footprints in the database can be spatially viewed, temporally constrained, and queried in order to help those in the GLIMS community quickly find ASTER imagery of interest. Statistics on the number and quality of ASTER scenes, grouped by Regional Center (RC) will also be presented. We examine yearly totals of ASTER acquisitions, broken down by percent cloud cover, for each RC's relevant ablation season. This information is crucial to understanding where suitable images currently exist, and for determining what regions require an increased priority in ASTER acquisition scheduling.

ABSTRACT 15

How accurately can we map tropical glaciers using satellite remote sensing?

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Presently, glaciers are scattered throughout the tropics and are found in the Andes, in three areas in Africa and in Irian Jaya on the island of New Guinea. These tropical glaciers are small; the largest inventoried tropical glacier has an area of under 20 km^2, the mean size of inventoried glaciers in the tropics is just over 0.6 km^2 and their median size is slightly over 0.1 km^2. The small size of tropical glaciers, their location in high relief areas and the persistent cloud cover of many areas of the tropics all contribute to the difficulty of accurately mapping tropical glaciers using satellite remote sensing.

The last remaining ice masses on Irian Jaya have been mapped since 2000 using IKONOS, ASTER and Landsat images. The extents of these small ice masses in 2000 and 2002 were determined from visual mapping of 1m IKONOS images within a Geographic Information System. Glacier extents have also mapped through visual analysis of both ASTER and Landsat images. Standard statistical classification methods, the normalized difference snow index (NDSI), and spectral unmixing have been applied to both ASTER and Landsat images to determine glacier areas in an automated fashion.

Using multiple approaches to map these ice masses has enabled a detailed comparison of how accurately and consistently small tropical glaciers can be mapped. Same day acquisition of Landsat and ASTER has allowed quantitative comparison of mapping between these two sensors, while comparisons with glacier area maps constructed from IKONOS images provides an assessment of the effect of resolution on mapping accuracy.

Overall, the areas of tropical glaciers determined from visual analysis of the two lower resolution sensors compare favourably to those mapped from the higher resolution IKONOS images. Moreover, glacier areas derived using standard statistical classification approaches and the NDSI compare favorably between sensors and with the IKONOS images adding confidence in applying these approaches to other areas of the tropics.

ABSTRACT 16

Problems related to the creation of a glacier inventory: Can we find consistent solutions?

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Those who already started to create glacier inventory data from remote sensing sensors (e.g. ASTER, ETM+, TM) encountered several methodological problems. While individual solutions have been found for technical problems (e.g. debris-cover, seasonal snow, shading), the methodological issues should be answered in the wider context of the interested parties (GLIMS, WGMS, GTN-G, CCS). The major question here is the definition of a glacier entity (i.e. what parts belong to a glacier?) with respect to space-borne observations. The proposed definition of a glacier (i.e. contiguous ice mass) as emerged during the GLIMS workshop in Twizel (NZ) is an excellent starting point, but the variable interpretation of the details would reduce the global usability of the derived data sets, if a general agreement on the details could not be found (e.g. perennial snow fields and rock glaciers have to be clearly identified in the datatbase to avoid confusion with real glaciers).

Some of the recognized methodological problems are:

- glacier types differ from region to region, causing different ways of defining the glacier basin (e.g. ice-ice divides on ice caps, contributing tributaries for valley glaciers)
- an older glacier inventory already exists (basins in analog/digital form available?, glacier split up) or not (how to start?)
- the purpose of the inventory influences the data handling (e.g. assessment of changes, modelling, GIS-based processing)

All these points have different implications for the delineation of glacier basins. For example, glacier volumes are overestimated when the area sum of all glaciers is used instead of the individual areas. Of course, the total area is required as well to follow the changes of a former contiguous ice mass. One important component to adress the differences in glacier basin delineation is the concept of a parent glacier as implemented in the GLIMS database at NSIDC. This concept allows to track changes for all parts of a multipart glacier (parts related in space) or a departed glacier (number of parts changed with time). As such, the concept already implies that two different parent glacier items (time and space) have to be tracked in the database. This and other related issues will be presented in the contribution and some first solutions are proposed that should be (and must be!) further discussed among the glacier mapping community.

ABSTRACT 17

The GLACE image comparison experiments

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GLIMS (Global Land Ice Measurements from Space) is an international collaborative project to map the world's glaciers and to build a GIS database that is usable via the World Wide Web. The GLIMS programme includes approximately 70 institutions, divided into 25 Regional Centers (RCs), who analyze satellite imagery, primarily ASTER and Landsat, to map glaciers in their regions of expertise. The analysis results from all RCs are collected at the National Snow and Ice Data Center (NSIDC) and ingested in to the GLIMS Glacier Database. A concern for future users of the database is data quality.

The process of analyzing imagery to extract vector outlines of glaciers has been automated to some degree, but there remain human-intensive stages to the process. To quantify the consistency of data provided by different Regional Centers, we have designed a method of comparative image analysis whereby several RCs and NSIDC analyze the same set of images, chosen to contain a variety of glacier types. The imagery is analyzed for glacier outlines and supra-glacial facies boundaries such as snow lines. The results are compiled, compared, and quantified for consistency. A matrix is developed to quantify inter-RC analysis consistency. This comparison, together with quality control steps applied before insertion into the database, leads to a better overall estimate of measurement reproducibility for mapping boundaries and facies boundaries for different types of glaciers within GLIMS. This talk will present the results of new analysis of data from both GLACE experiments, and will solicit discussion about future ones.

ABSTRACT 18

GLIMS: database status

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The Global Land Ice Measurements from Space (GLIMS) project is building a database of glacier outlines and other data that have been derived from high-resolution satellite imagery, resulting from analysis performed by GLIMS Regional Centers around the world. The project has made good progress in the last few years. There are currently approximately 70 Regional Centers, involving approximately 120 people. As of 2006-04-28, there are 51526 glacier "snapshots" in the GLIMS Glacier Database, and the rate of data ingest is accelerating. Each one of these glacier records includes a complete glacier outline and metadata about where the data came from. In many cases, many more data are included as well, such as vectors showing snow lines, World Glacier Inventory-compatible attributes, and information about debris cover, proglacial lakes, and supraglacial lakes.

Data in the GLIMS Glacier Database may be viewed interactively at http://glims.colorado.edu/glacierdata/, and searching by text fields and numeric constraints can be done at http://glims.colorado.edu/textsearch/. Data that are not under embargo may be downloaded in a number of formats from the same site.

With many researchers from many institutions contributing to the database, data quality is a concern. In order to quantify the variability of the glacier outlines produced by the GLIMS Regional Centers, we conducted two experiments where Regional Centers analyzed the same glaciers in the same satellite imagery. The resulting glacier outlines were sent to NSIDC for compilation and analysis for variability. Both experiments, called GLACE (GLims Analysis Comparison Experiment) 1 and 2, have made clear the need for use of topographic information in the analysis, precise definitions of how analyses should be done, as well as human verification of the results. Such protocols have been put in place. In addition, all GLIMS data submitted to NSIDC must pass a number of quality control (QC) steps before they are ingested into the database. Thus, the quality of data in the GLIMS Glacier Database is high.

ABSTRACT 19

Extraction and Evaluation of DEM Derived from the ASTER Stereo Data

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Grove Mountains called as “forbidden zone of the life”, is about 400-500km to the south of Zhongshan Station in Antarctica, its geolocation is about 73 degrees in South latitude and 77 degrees in East longitude. The area is about 8000km^2, which belongs to in-land ice sheet zone of the South Pole. The key area of Grove Mountains lies in 72°50′54″S-72°56′20″in South altitude ,74°54′07″E-75°14′09″in East longitude-its lengthen is 11km in west-east direction. Because it is the key area for the Chinese Antarctic scientific expedition, the topographic data in the area are necessary. Although the DEM of the entire Antarctic continent provided by RAMP was estimated that the highest horizontal (spatial) resolution is about 200m, the real horizontal resolution of the DEM varies from place to place according to the density and scale of the original source data. For ice shelves and the inland ice sheet, the horizontal resolution is about 1 km; the vertical accuracy is estimated to be ± 50 m. The conditions can not be satisfactory to further researches in Grove Mountains, so a DEM with higher horizontal and vertical accuracy is necessary.

The ASTER onboard the EOS-AM1 platform can offer nearly simultaneous capture of stereo images in along-track direction, minimizing temporal changes and sensor modeling errors. The VNIR subsystem includes two telescopes: a nadir-viewing telescope and a backward-viewing telescope, this dual-telescope can be used for generation of DEM with 30m spatial resolution. Generated DEM based on ASTER stereo data can be used to create contour maps and orthorectified imagery for the areas without any cartographic or topographic information like Antarctica at an unprecedented low cost, quick response and high resolution. The paper is introduced to create relative DEM based on ASTER stereo pairs without using ground control points. The final DEM result is compared to DEM surveyed in 2000 using GPS by Chinese surveyors, which indicates good accuracy and powerful usability of ASTER DEM construction in tough Antarctic in-land environment.

ABSTRACT 20

Tracing the *lines* of Icelandic glaciers: outline, equilibrium line, and firn line

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The area of temperate glaciers is one of their most important parameters in many respects, providing an indication of climate change, input to the aquifer, potential obstacles to the infrastructure, and basic source of hydropower. Despite the importance of glaciers in the Icelandic landscape and the hazard they pose to the community, general maps of Iceland have never portrayed the true areal extent of the glaciers, because the glacier outlines are commonly obscured in various ways. Moreover, most cartographers are not specially trained to identify glacier margins or to differentiate snowpack from glaciers.

The Hydrolgical Service of the National Energy Authority has now completed the project of tracing the outlines of all glaciers in Iceland
[http://gullhver.os.is/website/hpt/orkustofnun_english/viewer.htm].
They total 276 in number, and the area of the individual mountain glaciers and ice caps (and associated outlet glaciers) varies between 0.01 km^2 and 8,000 km^2. The total area was 11,048 km^2 in 2000.

The problems in identifying the glacier margin are as follows: debris on the termini of outlet glaciers and snow cover at higher elevations. Many small mountain glaciers may be completely covered with snow for extended periods, even for decades. This poses problems for automatic identification of glacier margins in Iceland on remote-sensing data. The outlines of most of the biggest ice caps were traced from satellite images (e.g., Landsat, SPOT), some from conventional vertical aerial photographs, but most of the smaller glaciers were drawn on 1:50,000-scale maps as determined from hand-held, stereoscopic pairs of oblique aerial photographs. In all cases, the identification of the glacier margin was aided by photographs taken at the optimum time seasonally: in the autumn and at the end of a warm summer.

Satellite images are excellent for tracing the transient snow line, which closely approximates the equilibrium line at the end of the ablation season. The firn line is also often easily detectable in late summer. The equilibrium line and the firn line are commonly confused in the literature. Because of tephra layers in Icelandic glaciers the difference between the two is, in many cases, obvious on satellite images. The firn line is very helpful in correctly identifying ice divides on ice caps. The establishment of ground truth is of utmost importance; it is commonly stated so in scientific papers but nevertheless many times omitted. Most of the glaciers of the world are remote and not easily accessible. That makes the need for checking on the ground or substantiation by other means even more important.

ABSTRACT 21

Recent Changes in Glacier Extent (1985-2000), Caucasus Mountains, Russia

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Glaciers occupy an area of ~1,600 km^2 in the Caucasus Mountains. There is widespread evidence of retreat since the Little Ice Age but an up-to-date regional assessment of glacier change is lacking. In this paper, satellite imagery (Landsat TM and ETM+) is used to obtain the terminus position of 113 glaciers in the central Caucasus in 1985 and 2000, using a manual delineation process based on a false colour composite (bands 5, 4, 3). Measurements reveal that 94% have retreated, 4% exhibited no overall change and 2% advanced. The mean retreat rate equates to ~8 m a-1 and maximum retreat rates approach ~38 m a^{-1}. The largest category (10 km^2) of glaciers retreated twice as much (~12 m a^{-1}) as the smallest category (1 km^2) of glaciers (~6 m a^{-1}) and glaciers at lower elevations generally retreated greater distances than those at higher elevations. Supra-glacial debris cover has increased in association with glacier retreat and the surface area of bare ice has reduced by ~10% between 1985 and 2000. Results are compared to declassified CORONA imagery from the 1960s and 1970s and detailed field measurements and mass balance data for the Djankuat Glacier, Central Caucasus. It is concluded that the decrease in glacier area appears to be primarily driven by increasing temperatures since the 1970s and especially since the mid 1990s. Continued retreat could lead to considerable changes in glacier runoff with implications for regional water resources.

ABSTRACT 22

ESA's GlobGlacier project

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The European Space Agency is starting a new activity related to glacier monitoring within its Data User Element programme (www.esa.int/due): the GlobGlacier project. The aim of this activity is to establish operational services for glacier monitoring from space, building upon, complementing and strengthening the existing services and network of global glacier monitoring (e.g. as conducted by the WGMS and the GLIMS project within the framework of the GTN-G). The targeted users of the service are, therefore, the science community studying glaciers in the context of climate change and the related international programs.

Glaciers from at least the following regions will be covered:

- Europe – Alpes
- Europe – North
- Africa
- Asia
- South America
- North America

The total number of glaciers monitored will depend strongly on the information to be monitored: from selected mass balance glaciers to "all" glaciers worldwide. Glaciers will be monitored over time, going back ten to twenty years.

The information products to be developed and demonstrated in the project shall respond to the operational needs and requirements of a certain number of users actively involved in the project. Additionally, these products should match requirements of the GCOS implementation plan for UNFCCC, and the GCOS document (under elaboration) "Systematic Observation Requirements for Satellite-based Products for Climate". Potential products are:

- Glacier outline maps
- Annual Equilibrium Line Altitudes or snow lines
- Topographic glacier parameters (Terminus altitude, mean slope, etc.)
- Flow velocity
- Time evolution of some of above features
- Other products suggested by the user community

ABSTRACT 23

The Western Canadian Cryospheric Network (WC2N): monitoring present and former glacier extents and volume changes

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The Western Canadian Cryospheric Network (WC2N) is funded (2006) by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) for the next five years. The network, centred at UNBC, includes 10 co-investigators from 6 universities in western Canada and one in the NW USA. Collaborators and partners include researchers from regional and federal government departments, institutions and organisations including GLIMS. The network goals are to:

1. document glacier extent and North Pacific climate variability (1600-2005),
2. detail meteorological processes and links to glacier nourishment and mass balance
3. model past and future changes to glacier cover in western Canada.

The first phase or 'theme' will map glacier extents and surfaces and determine rates of change in the western cordillera of Alberta and British Columbia through reconstructions: sub-decadal to 1985, decadal to 1950 and sporadic to 1900 when the first photographs and maps were produced. Data sources include extents and surface topography from Topographic maps, digital datasets, aerial photography, Landsat, SPOT, ASTER and SRTM. General changes in extent will be mapped for the whole region, with more detailed analysis in 7 selected areas. Earlier limits will be defined for the maximum of the Little Ice Age extent (ca. 1850) using geomorphic evidence and to 1600 AD using tree ring data. The results will be used as a base for themes 2-3 and as a contribution to GLIMS.

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Notes