Space-Based Mapping of Glacier Changes Using ASTER and GIS Tools

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***Abstract*—We describe an investigation that combines space-based observations of glacier parameters with historical glaciological data derived by traditional means to predict changes in ice extent and volume for the Ak-shirak Range in the interior Tien Shan of Central Asia. A variety of geographic information systems and photogrammetric tools are used to extract glacier outlines, derive of a digital elevation model, and compute area versus elevation distribution functions from data acquired by the Advanced Spaceborne Thermal Emission and Reflection radiometer. These products are then used in a glaciological methodology that can predict the response of glacier systems to changes in local climate.**

***Index Terms*—Geographic information systems (GIS), remote sensing, terrain mapping.**

I. Introduction

GLACIERS are a key indicator of climate change. Interest in worldwide monitoring of glaciers has grown as evidence of rapid glacier recession in many regions of the world is reported. The recognized need for a comprehensive assessment of the world's glaciers is driving efforts to devise and refine methods of extracting glacier information from satellite data.

While it is relatively easy to discern dramatic loss of glacier mass in high-resolution satellite imagery, understanding the processes that lead to this mass wastage and the ability to predict the conditions under which this may occur are more challenging. The objective of this study is to demonstrate one method of combining the products of satellite data analyses with *in situ* measurements to achieve some predictive capability in the study of mountain glacier systems.

II. Background

A. Glaciers and Global Change

Acceleration in worldwide glacier mass loss over the last few decades has significant implications for the ongoing rise in global sea level, water resources, and hydropower potential in many regions of the world. In addition, melting glaciers have a strong impact on water circulation and salinity, marine ecology, and fisheries, bringing economic impacts to Arctic coastal regions.

Increases in sea level and retreat of shorelines will have dramatic economic, political, and sociological consequences because more than 100 million people now live at an elevation within 1 m of sea level [1], and the number of people at risk may significantly increase [2]. Shoreline erosion due to sea-level rise is already creating significant problems in the Arctic and elsewhere [3]. Projections from the Intergovernmental Panel on Climate Change (IPCC) suggest a further rise of global sea level by an additional 0.5 m or so during the 21st century [4], [5], but the uncertainties in predictions are huge. The fraction of this rise due to glacier melt is currently a subject of vigorous debate. Published estimates suggest that the component due to glacier wastage may comprise 10% to 16% of sea-level rise over 1961–1987 [6], increasing to 27% since the end of 1980s [7]. This contribution may have further increased at the very end of 20th century as the wastage of large piedmont and mountain glaciers accelerated across Alaska and the Arctic [7], [8]. Clearly, this subject requires further study because the need to confidently project future sea-level rise is a pressing societal issue.

B. Remote Sensing for Assessment of Glacier Change

Because many glaciers lie in remote mountainous regions, remote sensing methods have often been employed in performing glacier surveys, beginning with aerial photography. Satellite imagery has been used in the study of glaciers for several decades (e.g., [9]–[12]). However, the ability to extract quantitative information from satellite data for use in computations of the annual net mass gain or loss of glaciers is still on ongoing challenge.

A primary objective in glacier studies is the determination of a glacier's total mass balance, defined as the total gain or loss in glacier mass at the end of the hydrologic year. This is the point in the local seasonal cycle, usually at the end of September in the Northern Hemisphere, where mass loss due to melting and sublimation has ended, and mass gain through precipitation has not yet begun.

The higher reaches of a glacier where there is a net mass gain is called the accumulation zone, and the lower reaches where mass is lost is called the ablation zone. The line that divides these two regions, i.e., the elevation at which mass is neither gained nor lost through the course of a hydrological year, is called the equilibrium line altitude (ELA). ELA is typically measured in the field by installing stakes at various elevations in

Manuscript received November 1, 2003; revised April 2, 2004. This work was supported in part by the National Aeronautics and Space Administration's Global Land Ice Measurements from Space Project under Grant NAG5-9722.

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Digital Object Identifier 10.1109/TGRS.2004.834636

the glacier and measuring the mass balance (i.e., the changes in snow/ice height at each stake) through the season. At the end of the season, the elevation at which there was no net gain or loss is identified as the ELA. The ELA is not something that can currently be directly measured from space. However, the characteristics of the glacier surface in the accumulation zone are distinct from those in the ablation zone, allowing some possibility of estimating the location of the ELA remotely. Specifically, the snow line altitude (SLA) divides the ice facies of the ablation zone from the snow facies of the accumulation zone. Since ice and firn[1] have lower albedo, 50% or less, than seasonal snow (albedo from 60% to 90%), there is a potential for determining the SLA remotely. If measured at the end of the melt season, the SLA is approximately coincident with ELA. If measured before the end of the melt season, the SLA may be lower than the ELA. In more polar regions, there is often an area with superimposed ice (refrozen melt water) below the SLA, making the ELA lower than the SLA.

Another glacier parameter related to a glacier's mass balance that has been the subject of research using satellite data is the accumulation area ratio (AAR). The AAR is defined as the ratio of the area of the accumulation zone of a glacier to its total area. If a glacier's outline is determined from georegistered satellite imagery, then its area can be computed. With a determination of the ELA the apportionment of area between the accumulation and ablation zones can be made, and thus the AAR determined.

Several studies have attempted to estimate snow line altitude (SLA) and accumulation area ratio (AAR) from sensors such as Landsat (e.g., [13] and [14]), sunthetic aperture radar (e.g., [15] and [16]), and the Advanced Very High Resolution Radiometer [17])], but the necessary validation data from field studies is often lacking. A recent study [18] showed excellent agreement between glacier mass balance determined by conventional field-based measurements and that estimated using remotely sensed ELA combined with glacier sensitivity to ELA changes determined also from field measurements.

The Global Land Ice Measurements from Space (GLIMS) project is using remote sensing data, primarily from the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) carried onboard the National Aeronautics and Space Administration (NASA) Terra spacecraft, and the Landsat-7 Enhanced Thematic Mapper Plus, to establish more reliably these techniques [19]. GLIMS will maintain a geospatial database of glacier information derived from ASTER and other space-based sensors. ASTER has improved spectral resolution compared to previous Landsat-class instruments. In addition, ASTER has adjustable gains, which is important for optimal imaging of snow and ice because the high reflectances of these surfaces frequently saturate the sensors in the visible bands (bands 1 and 2) when the gains are set normally, as for imaging vegetation, rocks, soils, etc. ASTER has been programmed for GLIMS to acquire data for all regions of the earth having permanent land ice using sensor gain settings adjusted to yield maximum detail over snow and ice surfaces [20].

[1]Granular, partially consolidated snow that has passed through one summer melt season but is not yet glacial ice.

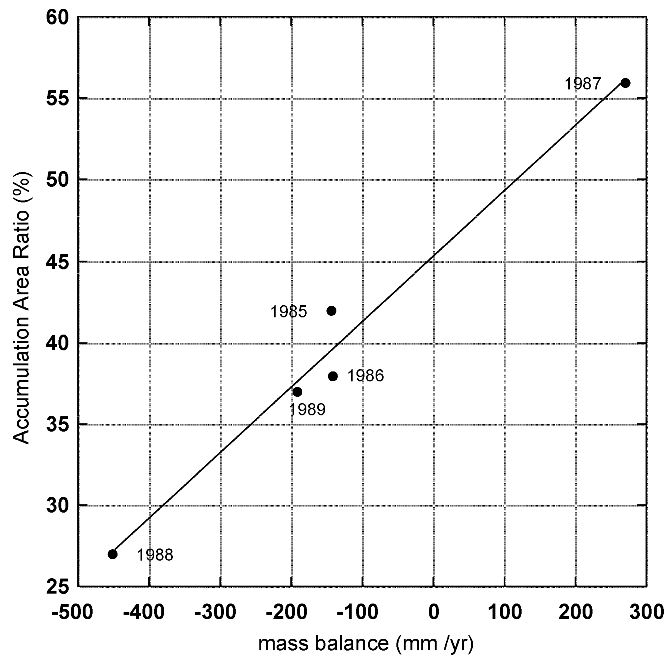

Fig. 1. AAR (percent) versus mass balance (millimeters per year water equivalent) for the Sary-Tor benchmark glacier.

C. Template Method for Estimating Glacier Mass Balance

Here, we provide a theoretical basis for relating remotely sensed glacier parameters to annual mass balance. The distribution of a glacier's surface[2] area over elevation is its hypsography, denoted here as $s(z)$. The value of the hypsographic curve at elevation z_i is the integral from the topmost elevation of the glacier $z_{\rm top}$ down to z_i, yielding the cumulative area A_i, expressed as a fraction of the total area of the glacier above that elevation

$$A_i = \frac{1}{A_{\rm tot}} \int_{\rm ztop}^{zi} s(z)dz \qquad (1)$$

where $A_{\rm tot}$ is the total area of the glacier.

The AAR is defined as the fraction of the glacier area that lies above the equilibrium line (ELA). The ELA is defined as that z_i where the mass balance b is zero $(b_i(z) = 0)$. The hypsographic curve allows us to compute how AAR varies with position of the ELA

$$\text{AAR(ELA)} = \frac{1}{A_{\rm tot}} \int_{\rm ztop}^{\rm ELA} s(z)dz. \qquad (2)$$

The annual mass balance of a glacier b_a is the specific mass balance $b_i(z)$ summed over all elevations of the glacier and over one year. Research has shown b_a to be a linear function of AAR (e.g., [21]). Fig. 1 shows this relationship for the benchmark[3] glacier, Sary-Tor, in the Ak-shirak Range of the interior Tien Shan of Central Asia. This can be expressed as

$$b_a = a_1 * (\text{AAR(ELA)} + a_2). \qquad (3)$$

[2]In glaciology, an hypsography is done using the "mapped" area of a glacier, i.e., the surface area projected to a horizontal surface.

[3]A "benchmark" glacier is selected as being representative of glaciers in a particular region and is setup for long-term monitoring.

The constants a_1 and a_2 are determined by fitting field measurements made over a period of several years to the above equation. We will assume this relationship applies to all glaciers in a region sharing a similar climatology.

By combining (2) and (3), one can calculate $b_a(\text{ELA})$, the annual mass balance for any ELA, given the empirically determined coefficients a_1 and a_2. This allows us to predict the response of a glacier's mass balance to any potential ELA that may observed at any time over the range of elevations occupied by the glacier. We define this relationship between annual whole-glacier mass balance $b_a(t)$, at time t, elevation z, ELA, AAR, and distribution of ice area by elevation $s(z)$ as the "template" for a glacier [22]. The method is described explicitly in Dyurgerov *et al.* [23], [24]. Note that the hypsography of a glacier changes much more slowly than the ELA, which can vary widely from year to year due to changes in local climate.

D. Stereoscopy With Satellite Images

The generation of digital elevation models (DEMs) from stereo images uses principles of photogrammetry first applied to aerial photography in the early 20th century. Stereoscopy is the process of creating a three-dimensional (3-D) model of an object based on the parallax between two images. An excellent review of the history of satellite photogrammetry is provided by Toutin [25].

ASTER is a Japanese instrument carried onboard NASA's Terra satellite. With its 15-m visible/near-infrared (VNIR) spatial resolution and along-track stereoscopy capability, ASTER is well suited to studying the earth's glaciers [26]. The two VNIR telescopes can be rotated up to 24° to provide extensive cross-track pointing capability and a five-day revisit capability. Along-track (same orbit) stereoscopy has advantages in terms of radiometric calibration, since observations are separated by minutes instead of hours as with multiple-orbit stereoscopsy.

We describe here an investigation that combines glacier outlines and a DEM, both extracted from ASTER data, to examine potential changes in mass balance volume for the Ak-shirak Range. This region was chosen because extensive glaciological mapping has been performed here since 1977, and an earlier glaciological map is available for 1943 [27], [28]. From ASTER data, we generate area-versus-elevation statistics using geographic information systems tools. When combined with field measurements for the benchmark glacier in this range, we are able to predict changes in glacier volume under varying climate forcings, realized as changes in equilibrium line altitude.

III. METHODOLOGY

A. Data Sources

The scheduling of ASTER image acquisitions is based on requests from researchers; areas selected by the ASTER Science Team for continual monitoring due to potential surface changes; and the goal of obtaining a one-time coverage of the entire land surface of the planet. For this research, two suitable ASTER Level 1A scenes were obtained from the NASA Land Processes Distributed Active Archive Center in Sioux Falls, SD: one from September 2001 and another from October 2002. The 2001 scene was used for digitizing glacier outlines, as described in [27], and the 2002 scene, which was more cloud-free and showed greater contrast for snow and ice surfaces, was used for the DEM extraction.

The *in situ* data consist of direct mass balance measurements of Sary-Tor, the benchmark glacier in the Ak-shirak Range. These measurements were carried out over the five-year period 1984–1989 [24].

B. DEM Generation

The production of a digital elevation model (DEM) from satellite imagery requires first a mathematical model that relates raw image coordinates to positions on the earth. This model must account for spacecraft location and velocity and sensor viewing geometry and integration time. In this study, we used a rigorous 3-D physical sensor model developed at the Canada Center for Remote Sensing (CCRS) [29], and applied it to bands 3N and 3B of the 2002 ASTER Level 1a scene discussed earlier. Radiometric corrections were first applied to the L1a data. We then used an automatic image-matching process to perform the stereo intersection and compute x, y, z coordinates in the Universal Transverse Mercator (UTM) projection. A pixel sampling of 2 was used to create a DEM with 30-m postings.

Tie points are used to help the automated image matching process. We chose features that could be clearly identified in both the 3N and 3B images, such as stream confluences and rock outcroppings. Twelve tie points, distributed approximately evenly over the scene, were selected.

Ground control points (GCPs) provide input to the sensor model by tying image location to ground location. Lacking high-accuracy GCPs for this region, such as would be obtained by global positioning system surveys, we extracted GCPs from a 1956 1 : 100 000 scale topographic map. The map was scanned at 300 dpi, or an 85-μm dot pitch, which is equivalent to 8.5 m on the ground. The map was registered to a UTM grid using the four corner points and one center point. Ground control points were then read off the map and matched to features in the ASTER 3N and 3B scenes. These control points included rocky summits and other features that were determined to not have changed significantly since the map was made. Elevations were assigned 5-m uncertainty, and x, y positions were given a 30-m uncertainty. A total of six ground control points were used in this analysis.

Orthorectification is the process of correcting the distortions in imagery introduced by topography. We have found that areas of high relief displacements, as a large as 300 m, may be present in ASTER images. We used the DEM we generated to orthorectify the visible band images. When these are draped over the DEM, perspective images can be generated, such as that shown in Fig. 2.

Outlines of 176 individual glaciers in the Ak-shirak range were hand digitized from the 2001 ASTER scene (see [27] for a description of the methodology). For the present analysis, the digitization was checked by redigitizing the Petrov glacier, which represents about 30% of area of Ak-shirak system, on the orthorectified 2002 image. To do the digitization, we used the newly developed GLIMSView software. GLIMSView was developed under the GLIMS project ([19], see: http://www.GLIMS.org). It is distributed freely and runs

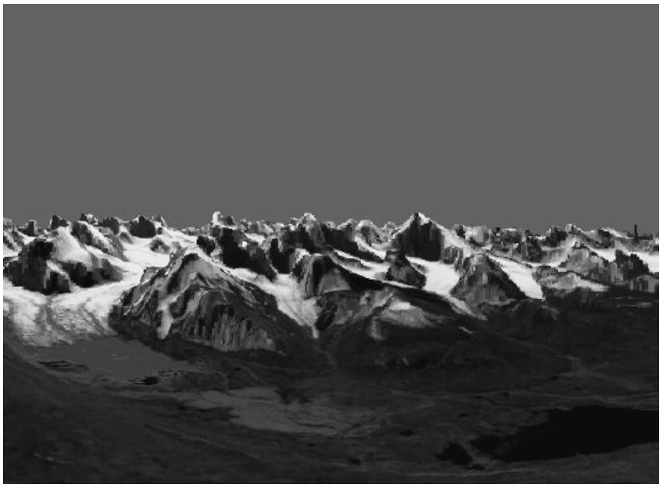

Fig. 2. Perspective view of the Ak-shirak Glacier system. This is a grayscale version of an image produced by draping a ASTER Bands 3N, 2, and 1 in false-color Red–Green–Blue composite over the DEM generated in this analysis. A portion of the Petrov glacier, with a proglacial in the foreground, is seen in the leftmost portion of the image. The Sary-Tor glacier occupies the third valley to the right from the lake.

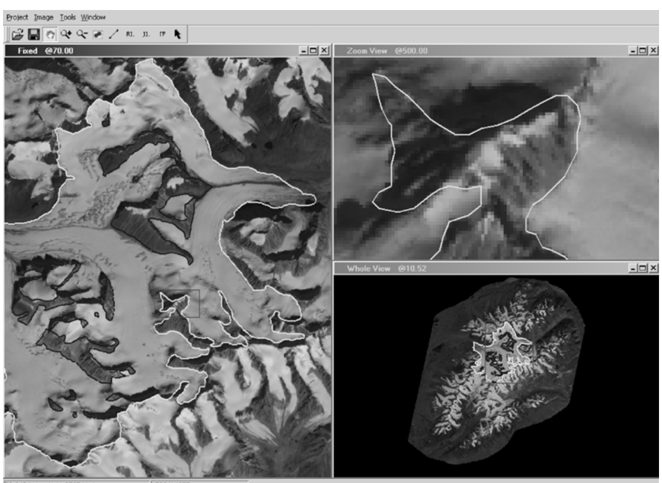

Fig. 3. Glacier outlining using GLIMSView.

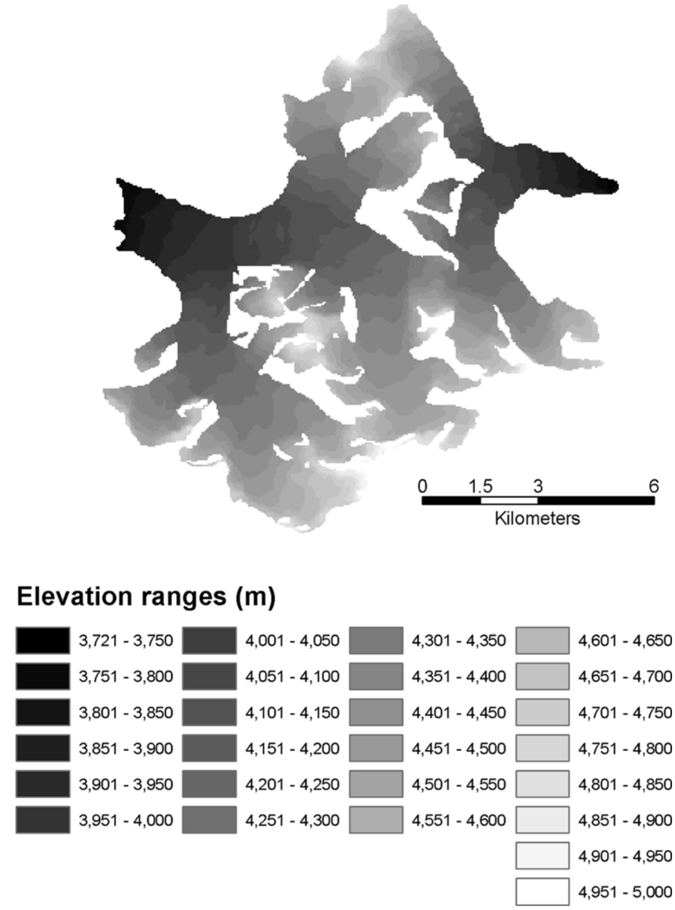

Fig. 4. Distribution of elevation in 50-m intervals for the Petrov glacier system in Ak-shirak Range.

on most popular computer platforms. One of its main features is that it exports the results of glacier analyses in the format that is specified for ingest into GLIMS database at the National Snow and Ice Data Center. Fig. 3 shows the process of outlining the Petrov glacier using GLIMSView.

The hypsography obtained using the outline of the Petrov glacier made from the 2001 image differed by no more than a few percent with a hypsography made from the 2002 image for this glacier, so the 2001 outlines for the whole of the Ak-Shirak were applied to generate the hypsography used in this analysis.

C. Hypsography

As described in Section II-C, the "template" for a glacier is the function that describes relationship between its mass balance and all possible equilibrium line elevations. The approach of relating mass balance to ELA has been widely used (e.g., [30]) but has not been explicitly related to the glacier hypsography, $s(z)$, as described here. The basic assumption here is that within a climatologically similar region, differences in mass balance between glaciers in this region are due to primarily to differences in glacier surface topography and elevation, i.e., the hypsography. Other parameters such as aspect, distance from orographic barriers, and topographic shadowing may also be important in the determination of glacier's mass balance, but these factors are all linked to the topography and will be reflected in the distribution of glacier mass with elevation.

To apply the template method described in Section II-C, we first determined the hypsography for the Ak-shirak using the 2002 DEM, combined with the 2001 glacier outlines. The polygons outlining each of the 176 glaciers were converted to a grid whose cells were mapped to the DEM. The grid points covered by each glacier polygon were assigned an ID number unique for that glacier. Any grid points falling within internal polygons outlining exposed rock were excluded. An area-by-elevation histogram (i.e., the hypsography) was obtained for each glacier by counting the number of pixels in 50-m elevation bands having a particular glacier identification. The distribution of elevations for the Petrov glacier is shown in Fig. 4. The hypsography for the glacier system as a whole was obtained by summing all pixels in each elevation band. Pixel count was converted to area using a DEM pixel area of 900 m^2.

IV. Results

A previous study of the Ak-shirak Glacier system found that ice area decreased by 20% between 1977 and 2001, following only a 3% decrease from 1943–1977 [27]. It should be noted that some of the reported change may involve only differences in interpretation of glacier boundaries between the 1977 glaciological survey and the 2001 satellite image analysis. For the present study, we will use the satellite-determined hypsography to evaluate this 20% areal change in terms of glacier mass balance, or volume change $\Delta\mathbf{V}$.

Field measurements of the Sary-Tor benchmark glacier were used to find annual mass balance as function of accumulation area ratio (Fig. 1). This relationship is assumed to apply to all glaciers in the Ak-Shirak range, since they share a similar climate, terrain, etc. The integral of the area versus elevation curve gives AAR as function of ELA for any glacier (see (2) in Section II-C). Using a glaciers's hypsography, we can get $b_a(\text{ELA})$ (see (3) in Section II-C), expressing mass balance as a function of ELA. This curve, unique to each glacier, allows us to estimate the mass balance for that glacier using only the observed ELA. Similarly, the mass balance for the entire Ak-Shirak system can be estimated using the hypsography computed from the 176 glacier outlines and the DEM.

Thus, using the template method, we calculate the relationship between glacier mass balance for the aggregate Ak-shirak range and ELA. For comparison, we perform the same calculation using a historical hypsography based on topographic maps made in the latter part of the 1970s [28].

We express our final result as the change in volume of the glacier system (in water equivalent) for a given ELA (Fig. 5). This is calculated by integrating $b_a(\text{ELA})$ over the area of the glacier

$$\Delta V(\text{ELA}) = \int_A ba(\text{ELA})dA. \tag{4}$$

In practice, (4) is computed by summing the product of the mass balance at a given ELA and the glacier's area in that elevation band. This is "potential" ELA that can be observed at time t in the whole range of elevations occupied by glaciers in Ak-shirak Range (3650–5125 m).

A. Error Analysis

There are several factors contributing to the uncertainty in predictions of glacier mass balance as a function of ELA using the template method. First, the error in the computation of mass balance from field measurements of Sary-Tor glacier may be as much as ± 150 mm/year. For the remotely sensed variables, there is the uncertainty in the determination of glacier boundaries, which we estimate to be within two ASTER pixels, or 30 m. Also affecting the hypsography is the error in the ASTER DEM. DEMs derived from ASTER stereo pairs have been estimated to have vertical accuracy of 15–20 m in regions of rugged topography [29].

Using (3), we translate an error in ELA of ± 15 m into an error in annual specific mass balance of about 54 mm/year. Combining this with the uncertainty in measured mass balance of ± 150 mm/year, assuming independent, randomly distributed errors, we get a total error of about ± 160 mm/year in predicted mass balance. In terms of predicted volume change, this translates into an error of 0.006 km^3 at the ELA for which there is the maximum volume gain (4300 m or 6%).

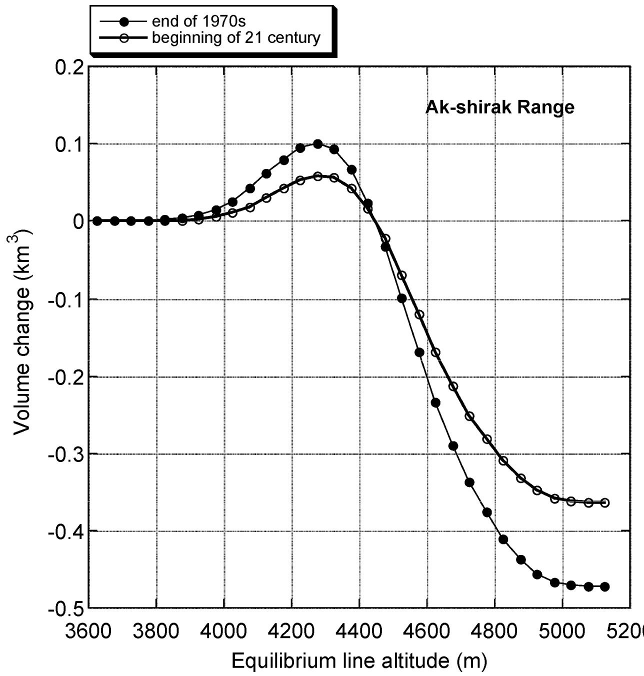

Fig. 5. Projected volume change (water equivalent) versus equilibrium line altitude (ELA), for all glaciers in the Ak-shirak Range, for the 1970s (period 1) and early 2000 (period 2).

The uncertainty in the fitting of AAR to mass balance measurements with only five data points (Fig. 1) is not a major contributor to the overall error, as the correlation coefficient of 0.97 justifies rejecting the null hypothesis at the 1% level of significance.

Finally, we have assumed that observations at Sary-Tor are representative of the entire Ak-shirak range. This assumption is not as unwarranted as it might seem. For the template method to apply, we need only for the mean meteorological and energy balance conditions to vary across the range in a similar manner on an interannual basis. Validation of this assumption will be the subject of future studies.

V. Discussion and Conclusion

Fig. 5 shows that the manner in which glaciers in the Ak-shirak range respond to climate variability has changed dramatically between the early 1970s and the present. This change is entirely due to changes in glacier perimeters and the distribution of glacier area over elevation. These relationships may be used to predict the extreme values of glacier volume change, in terms of water stored (positive values) or water released (negative values).

The $\Delta V(\text{ELA})$ curves (Fig. 5) for period 1 (end of 1970s) and period 2 (2000–2001) cross the zero level at the elevation of about 4450 m. If the ELA is below 4450 m, the glacier system is gaining mass. If the ELA is above this level, the system is losing mass. Fig. 5 shows that the process of volume change with elevation is not linear, but varies according to the glacier hypsography.

At the highest level (around 5 km above sea level), the ELA may only appear in extreme warm and dry years. Such extreme climate conditions have never been observed in this region over the period of instrumental studies from 1930 until 1998, according to the meteorological observations at the nearby meteorological station "Tien-Shan" (5 km to the north from the Ak-shirak Range at the elevation 3614 m). Loss of glacier volume computed from Fig. 5 can be interpreted as additional melt-water inflow from the Ak-shirak Range to the local river basin, which feeds Naryn-Syr-Darya-Aral Lake.

ELA (or its surrogate SLA), in principle, can be determined from summer images [17], [18], although we have not attempted this with the images in hand. Both the September 2001 and the October 2002 ASTER images have no distinct change in albedo with elevation, probably due fresh snowfall late in the melt season. We hope to obtain satellite imagery from a late-summer period, which will allow us to compute a snow line altitude.

In conclusion, we have shown that the response of glacier systems to changes in climate, expressed in the equilibrium line altitude, can be estimated using a combination of ASTER data and traditional glaciological measurements. The spatial and spectral resolutions of ASTER, and its along-track stereo pair capability, make this instrument well suited to studying the earth's glaciers.

Future GLIMS work will include performing fieldwork to validate transient snow and equilibrium line determination from satellite data and the overall "template" approach to estimating mass balance. We will also plan to evaluate anticipated glacier volume change in response to various climate scenarios, along with estimates of contributions to sea level rise.

Acknowledgment

The commercial software packages PCI Geomatica and ESRI's ArcGIS were used in the course of this work. The first author is grateful for the support received from W. Vroom (PCI). The authors also thank V. Kuzmichenok and V. Aizen for supplying topographic maps.

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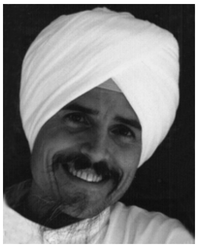

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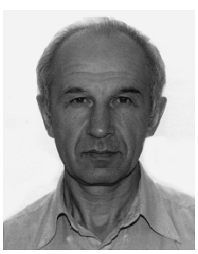

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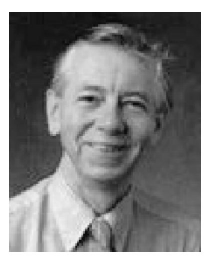

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