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Space-based assessment of glacier fluctuations in the Wakhan Pamir, Afghanistan

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Abstract Alpine glaciers directly and indirectly respond to climate and play a significant role in mountain geodynamics. Many glaciers around the world have been found to be retreating and downwasting, although these patterns are highly variable due to variations in local topography, regional climate and ice-flow dynamics. Unfortunately, limited information is available on glacier fluctuations in the Wakhan Pamir of Afghanistan, and no data exist from there in the World Glacier Monitoring Services (WGMS) database. Our general circulation model (GCM) climate simulations represent a double carbon-dioxide-loading scenario, and results suggest that glaciers in this region should be downwasting and retreating. Therefore, as part of the Global Land Ice Measurements from Space (GLIMS) project, we evaluated ASTER and Landsat MSS data to assess glacier fluctuations from 1976–2003, in the Wakhan Corridor of Afghanistan. We sampled 30 alpine valley, compound alpine valley or cirque-type glaciers of varying size and orientation. Results indicate that 28 glacier-terminus positions have retreated, and the largest average retreat rate was 36 m $year^{-1}$. Satellite image analysis reveals non-vegetated glacier forefields formed prior to 1976, as well as geomorphological evidence for apparent glacier-surface downwasting after 1976. Climatic conditions and glacier retreat have resulted in

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disconnection of tributary glaciers to their main trunk, the formation of high-altitude lakes, and an increased frequency and size of proglacial lakes. Collectively, these results suggest increased hazard potential in some basins and a negative regional mass balance.

1 Introduction

Alpine glaciers directly and indirectly respond to climate forcing and are now known to play a significant role in mountain geodynamics (Bishop et al. 2004). In Afghanistan and many other countries, alpine glaciers represent a vital source of water, and glacier fluctuations regulate water-resource availability. Anticipated changes in temperature and precipitation patterns caused by climatic warming pose a significant threat to the economic and geopolitical stability of many regions. Furthermore, climbing temperatures and increasing melt water will contribute to the current rise in sea level. Consequently, an international effort (GLIMS) to assess glacier fluctuations around the world has been initiated (Bishop et al. 2004; Kargel et al. 2005).

There are, however, very few direct observations of the glaciers in Afghanistan (Shroder and Bishop 2007). In the Wakhan Pamir of Afghanistan, very little quantitative data on glacier fluctuations have ever been reported, because of complex topography, paucity of field measurements, and geopolitical restrictions. Therefore, the WGMS database does not have any entries for glaciers in this region for comparison purposes. A limited number of glaciological studies, however, have been conducted and include the work of Gilbert et al. (1969) on small glaciers near Mir Samir in the central Hindu Kush, Braslau (1972) on the Keshnikhan Glacier in the Wakhan Hindu Kush, Breckle and Frey (1976a, b), who noticed relatively strong glacierization facing the east and southeast near the Pakistan border, and the beginnings of a glacier inventory of Afghanistan for the WGMS by Shroder (1980, 1989), who used incomplete sets of aerial-photo-derived, small-scale maps to study glacier distributions. Given the current geopolitical instability of Afghanistan, space-based assessment of glaciers in the Wakhan Pamir is the only practical approach for monitoring glacier fluctuations.

Our research objective is to report on glacier retreat patterns in this region, as this research is part of the International GLIMS project. We specifically wanted to determine how the glaciers in the Wakhan Corridor of Afghanistan are responding to climate change. To accomplish this, we conducted GCM climate simulations to characterize past, present and future climate conditions that can provide insight into glacier responses. We then analyzed Landsat MSS 1976 and ASTER 2003 data to estimate glacier retreat rates and evaluate changes in surface hydrological conditions caused by melting snow and ice.

1.1 Previous research

Austrian investigators (Patzelt 1978) conducted research in 1974 and assessed: (1) glacier orientation; (2) maximum and minimum altitudes; (3) maximum length; (4) total area and debris-covered area; (5) glacier hypsometry; (6) glacier area changes;

(7) transient snow lines (TSL) and lateral-moraine altitudes; (8) daily ablation rates on South Issik Glacier; and (9) areas of newly exposed glacier forefields (recent retreat areas directly below the existing terminus zones).

Soviet and Russian interest in the glaciers of Afghanistan has been intensive for some time, in part because of the melt-water resources that flow out of Afghanistan to the north. The World Atlas of Snow and Ice Resources (Kotlyakov 1997) is at a small scale of 1:5,000,000 but is still useful for assessment of the Wakhan. For example, solid precipitation was mapped at 400–800 mm, and the duration of the warm season (number of days >0°C) was <60 in the Wakhan Pamir. Average air temperature in summer was estimated to be about 0°C to −1°C on the north side of the Pamir range, whereas it was 0°C to 1°C on the south side. The number of days with snow cover was 200–>300; with snowbanks lasting ~6 months (Tsarev et al. 1986). The proportion of glacier melt water in the annual runoff was judged to be about 80% in the Ab-i-Panj from glacier locations in the Wakhan (Kotlyakov and Lebedeva 1998). Kravtsova and Tsarev (1997) also assessed snow cover and avalanches throughout Afghanistan and the Wakhan Corridor.

Porter (1985) used Landsat imagery to determine the extent of Late Pleistocene glaciers in Afghanistan. He roughly determined equilibrium line altitudes (ELAs) but Kotlyakov and Lebedeva (1998) noted more precisely that in the Pleistocene these altitudes were at about 4,300–4,500 m in the Wakhan Pamir. For better predictions of future conditions Lebedeva (1997) assessed potential changes of glacial runoff of Hindu Kush rivers, using empirical and statistical forecasts of regional increases of temperature by 0.5°C and precipitation by 12–15%, to produce a diminution of glacier melt water of some 13–21%.

2 Study area

The Wakhan Corridor is located in the highest part of the Greater Pamir (Fig. 1). The study area exhibits nine peaks >6,000 m, that are composed largely of resistant, light-colored granitic rocks of late Cretaceous–Tertiary age, intruded into Asian continental shelf sediments that are now metasedimentary rocks, with black argillite and slate as prominent types (Buchroithner 1978). The extensive high altitudes permit the growth of some of the largest glaciers in Afghanistan, despite the fact that the mean annual precipitation there is scant (Lalande et al. 1974). The melt waters from these glaciers give rise to the major Pamir, Wakhan, and Ab-i-Panj tributaries to the Nile-sized Amu Darya River that constitutes much of the north border of Afghanistan.

The general climate in northeastern Afghanistan is controlled in large part by its continentality far from moderating oceanic temperatures and moisture sources, which makes it cool to cold, with only limited precipitation. The WMO (1981) estimate of mean annual air temperature in the mountains of the Wakhan Corridor was −5°C to −10°C. Grötzbach (1990), using data from Lalande et al. (1974), mapped mean annual precipitation in the Wakhan at <100 mm in the lower valleys and up to 300 to <500 mm in the Wakhan Pamir. The timing of this precipitation is >50% in spring, with some 10–35% in May and June. Summer monsoonal precipitation that commonly gets to the higher mountains of Nuristan and sometimes into the central Hindu Kush, rarely ever reaches the Wakhan (Sivall 1977; Grötzbach 1990).

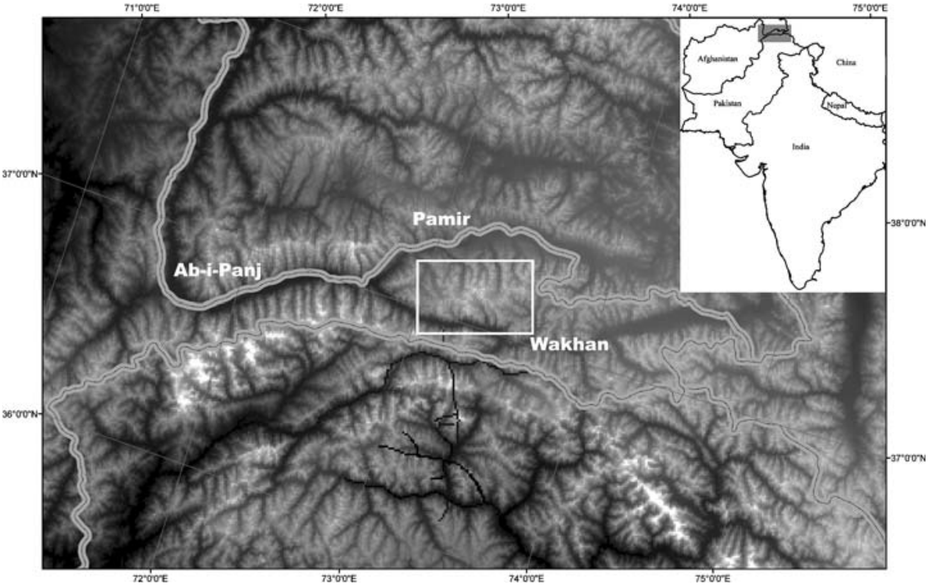

Fig. 1 Location map of the study area in Afghanistan. The *white rectangle* denotes the Wakhan Pamir region. Names of the main rivers associated with the study area are presented in *white letters*

In contrast to the WMO (1981) estimates, the NCEP/NCAR reanalysis data are a synthesis of worldwide observations passed through a numerical climate model to deliver a climatological dataset on a global, regular grid of 2.5 × 2.5° horizontal resolution (NCEP Daily Global Analyses data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/). Data from the reanalysis averaged over the past 20 years indicate mean annual temperatures in the Wakhan Corridor ranging from −10°C in the western part of the Corridor to −16°C in the eastern part (Fig. 2a). Most of the Corridor lies in the rain shadow of the Hindu Kush with annual mean precipitation less than 200 mm/year in the east with slightly greater values in the western part of the Corridor (Fig. 2b).

3 GCM simulations

We use a numerical GCM to examine past, present, and future climate conditions. A coupled atmosphere-ocean GCM simulates the climate in this region during the Holocene, modern-day conditions, and for a hypothetical climate in which the atmospheric carbon dioxide levels are double the pre-industrial value. The atmospheric and oceanic models were developed at the Geophysical Fluid Dynamics Laboratory in Princeton, NJ, and the atmospheric component has a spatial resolution of 3.75° in longitude by 2.25° in latitude. The model includes a full hydrological cycle with a moist convective adjustment scheme for parameterizing cumulus convection. A surface energy-balance scheme takes into account all hydrological variables, including soil moisture, as well as net short-wave and long-wave fluxes. The atmosphere

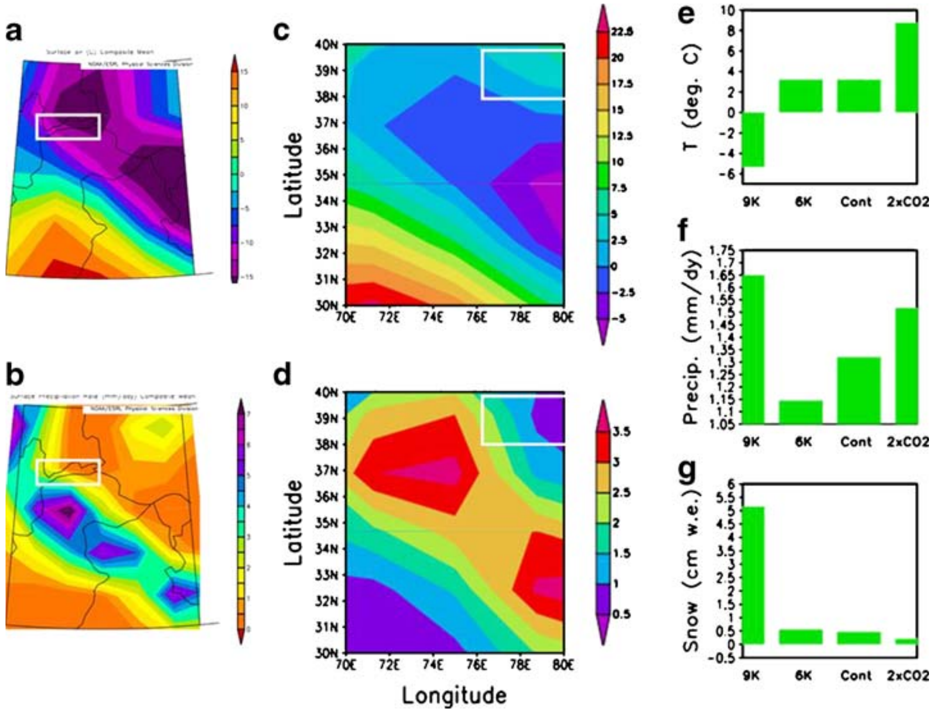

Fig. 2 NCEP/NCAR annual-mean reanalysis data are for the period 1987–2006 of **a** surface air temperature (°C) and **b** precipitation (mm/day). The *white rectangle* denotes the approximate location of the Wakhan Corridor. GCM results are for present day **c** temperature (°C) and **d** precipitation (mm/day). The *white rectangle* denotes the area over which spatial averages are computed (see text for details) to plot the histograms of **e** temperature (°C), **f** precipitation (mm/day), and **g** snow accumulation (centimeters water equivalent) for the Holocene and future climate scenarios. The acronyms for the 9*k*, 6*k*, and $2xCO_2$ are 9,000 B.P. 6,000 B.P. and doubled CO_2 simulations, respectively

and ocean models communicate once each day, passing between them the required boundary conditions (see Bush 2007 for more details).

Results for the region are in broad agreement with the observational data in that the mountains of the area induce low annual mean temperatures and high values of orographic precipitation (Fig. 2c, d). However, the relatively coarse spatial resolution of the GCM implies that the topography of the Hindu Kush, the Pamir, and the entire Himalaya are smoothed in order to be compatible with the model's spectral resolution. Differences in the exact location of topography must therefore be taken into account when comparing GCM results to actual data (as in Fig. 2a, b). For this reason, the following discussion of simulated climate changes uses a spatial average over a geographic region that is different from the latitude-longitude boundaries of the actual Wakhan Corridor, but which lies in the rain shadow of the model's smoothed Hindu Kush. Despite this limitation, model biases are consistent between simulations of various time slices so insight may be gained into regional climate change due to changes in orbital and greenhouse-gas forcing.

Results from simulations configured for 9,000, and 6,000 years ago, and a carbon dioxide forcing scenario (Fig. 2e–g) indicate that 6,000 years ago conditions were approximately similar to today with slightly less precipitation. At 9,000 years ago, when Earth's obliquity was high (e.g., Berger and Loutre 1991) and atmospheric carbon dioxide was approximately 264 ppmv (Indermühle et al. 1999), simulated climate was significantly colder with higher values of precipitation than today (both rainfall and snow). In a climate with doubled modern carbon dioxide, temperatures are 4–5°C warmer than today with increased precipitation and reduced snow accumulation. Simulated climate for the region therefore suggests that from the early Holocene to today and into a hypothetical future, a long-term glacier retreat trend should exist and continue to increase in magnitude, assuming increased temperatures and no increases in snow accumulation. We recognize, however, that short-term glacier fluctuations would correspond to climate forcing, even though our climate simulations only represent the range of natural variability for the climate of the region.

4 Snowline, equilibrium line or glaciation threshold

The relative paucity of precipitation in the Wakhan Corridor causes the altitudes of permanent snow and ice to remain at fairly high altitude. von Wissman (1959) assessed the snow lines (or firn line, which on temperate glaciers like these, is also considered to be a reasonable proxy of the equilibrium line) of Asian mountains, and his analysis put the line or zone that separates ice from firn and snow at the end of the melt season at ~5,300 m in the Great Pamir. A nearby glacier in the Wakhan Corridor, the Yamit, was noted by Zabirov (1955) to have a snowline of ~4950–5,000 m. The Austrian team in 1974 in the Wakhan Pamir mapped a variety of transient snow lines (TSL) in the first half of August, 1975, ranging from a low of 4,800 m to a high of 5,420 m.

Many remote-sensing studies of glaciers and snowlines use subjective approaches and do not orthorectify or radiometrically calibrate their data. We developed a semi-automated approach for snow-line detection that integrates multi-temporal normalized-difference-snow indices (NDSI) and a digital elevation model (DEM). The ASTER-generated DEM is referenced as a baseline altitudinal map. The DEM is first used to orthorectify multi-spectral imagery to remove topographic distortion at the pixel level (Bishop et al. 2004). The orthorectified images were radiometrically calibrated by converting image digital numbers (DN) to radiance. The calibration removes system gain and offset effects. Radiance images were used to generate NDSI images that enhance snow and ice, and reduce the effects of viewing geometry and atmospheric conditions (Salomonson and Appel 2004; Gupta et al. 2005). Image segmentation demarcated snow boundaries. Specifically, we use a NDSI threshold value of 0.9 for each multi-temporal dataset. We then compared snow maps with the DEM reference image using Boolean logic to obtain an estimate of the snow-line altitude.

Based upon a sampling of 25 glaciers, our analysis suggests an average maximum TSL altitude of ~5,079 m (25 July 2003 ASTER imagery). The ~19 TSL measurements made by the Austrians in August 1974 averaged 5,128 m. This is relatively equivalent to the average heights of the highest exposed lateral moraines at ~5,102 m, and the highest exposed medial moraines at ~5,200 m. Our value is not significantly different than the value obtained 27 years ago, although a higher snowline altitude would result from an analysis of imagery acquired at the end of the ablation season.

Our transient snow line (minimum 4,850 m; maximum 5,280 m) results are highly variable because of several factors: (1) the ASTER imagery was not acquired at the end of the ablation season; and (2) anecdotal (Braslau 1972) and satellite evidence show that new snow can occur in all months in the Wakhan. We conclude that we have not systematically accounted for seasonal variation in snow line due to the difficulty of obtaining satellite imagery for each month of the ablation season and at the very end of the ablation season. More research is required to accurately characterize changes in the seasonal variability of snow-line altitude through time.

5 Glacier retreat

A satellite-based assessment of glacier termini positions was conducted using Landsat MSS (09 August 1976) and ASTER (25 July 2003) data. The MSS data were ortho-rectified with a root mean square (RMSE) of 14.94 m. The ASTER scene was also used to estimate other glacier parameters (Table 1). Data prior to 1976 are not readily available, although a topographic map made by Austrians in 1974 does exist. Using maps by the Austrians and Soviets is highly problematic as spheroid and datum information is not readily available, and the Soviets had altered datum information, which makes analytical comparisons impossible (i.e., similar points on the ground will not have the same coordinates, and the biases may vary spatially). Other satellite imagery exists, although snow-covered scenes do not permit identification of terminus positions.

Our retreat results (Table 1) over a 27 year period indicate that twenty eight out of the 30 alpine valley, compound alpine valley or cirque-type glaciers sampled are retreating, with an average retreat distance of 294 m (minimum 3 m; maximum 991 m). The accuracy of our results is on the order of ±1 MSS pixel (57 m) because the glacier terminus was easily identifiable in the imagery. Retreat distance variability is high, and many large glaciers appear to have retreated more than the smaller glaciers. We did not find a relationship between terminus altitude and retreat rate. For example, eight large glaciers (Eastern Bey Tibat, Western Bey Tibat, Eastern Ali Su, Western Ali Su, Zemestan, Ptukh, AF5X14230076 and AF5X14231002) exhibited the greatest retreat distances. In addition, a large compound valley glacier, Northern Issik, has retreated and become a single valley glacier, as its five tributaries have detached and are now five independent glaciers. Three of these tributaries are retreating at an average rate of 34.6 m (AF5X14231003), 23.7 m (AF5X14231002), and 6.8 m (AF5X14231001). Another separated tributary glacier exhibits geomorphological patterns of apparent downwasting, and a new high-altitude pro-glacial lake has formed due to lowering of the terminus area (Fig. 3). Due to this thinning, the lateral moraine of the main glacier acts as an end moraine for the detached tributary glacier.

Image analysis also reveals that the larger glaciers with high average retreat rates exhibit relatively thin debris cover over visible ice, which can enhance ablation. Smaller glaciers at higher altitudes do not have as much debris cover. Glaciers with a lower-average recession rate commonly exhibit signs of apparent surface

Table 1 Sampled alpine glaciers in the Wakhan Pamir, Afghanistan

Glacier				Location		Terminus position			
ID	Name	Azimuth	Area (km^2)	Latitude (37° N)	Longitude (73° E)	Latitude (37° N)	Longitude (73° E)	Altitude (m)	Annual retreat (m/year)
AF5X14220057	–	NW	3.1331	13′37.06″	27′59.04″	14′19.54″	27′05.67″	4,676	6.9
AF5X14220061	–	N	7.5597	12′35.14″	23′38.38″	14′15.17″	24′03.14″	4,645	3.9
AF5X14220080	–	NW	2.4417	09′06.97″	22′32.24″	09′36.71″	21′36.37″	4,747	6.0
AF5X14220081	–	N	2.9600	08′22.59″	21′20.30″	09′12.74″	21′11.03″	4,804	0.0
AF5X14220083	Tila Bey	NE	20.4291	08′14.49″	18′24.04″	10′08.57″	20′25.13″	4,387	3.3
AF5X14220084	–	E	3.7308	10′39.05″	18′16.59″	11′04.56″	19′34.02″	4,718	7.2
AF5X14220100	Eastern Bey Tibat	N	9.4084	11′00.64”	16′20.91″	13′00.10″	15′51.78″	4,600	11.4
AF5X14220105	Western Bey Tibat	N	11.1563	10′00.00″	13′00.89″	12′06.80″	13′06.90″	4,541	36.7
AF5X14220117	Eastern Ali Su	N	6.1749	09′44.75″	10′52.31″	11′43.58″	10′44.62″	4,690	30.2
AF5X14221001	West Little Ali Su	NE	3.5664	05′35.03″	07′20.58″	06′52.63″	07′19.96″	4,819	4.8
AF5X14221002	East Little Ali Su	NE	3.8227	06′07.04″	06′33.03″	06′52.85″	07′49.12″	4,810	0.0
AF5X14221003	Western Ali Su	N	16.1968	05′35.02″	08′52.70″	07′29.70″	08′27.11″	4,620	14.2
AF5X14221004	West Issik	E	2.2177	07′23.35″	10′34.82″	07′51.47″	09′20.99″	4,776	11.0
AF5X14221005	–	W	4.5687	08′13.56″	11′32.69″	08′09.69″	09′42.28″	4,857	4.3

AF5X14221006	–	W	1.6293	10′02.39″	23′12.47″	09′56.84″	22′25.20″	4,922	3.9
AF5X14221007	–	SW	1.4439	10′53.30″	23′29.83″	10′26.91″	22′51.30″	5,005	6.7
AF5X14230029	Zemestan	E	5.2316	03′09.60″	14′09.24″	03′10.84″	16′01.58″	4,804	17.0
AF5X14230038	Ptukh	SE	7.1872	06′26.57″	18′27.36″	05′20.10″	19′09.41″	4,911	18.6
AF5X14230072	–	NE	0.8426	04′14.40″	24′48.14″	04′42.59″	25′01.35″	4,863	1.3
AF5X14230073	–	NE	1.4306	04′29.67″	24′21.54″	05′10.03″	24′37.70″	4,835	2.8
AF5X14230076	–	E	5.6955	06′40.30″	21′28.16″	06.27.90″	22′49.72″	4,804	18.4
AF5X14230086	–	SE	3.2758	11′18.24″	24′09.01″	10′43.91″	25′15.10″	4,872	8.3
AF5X14230091	–	S	3.8039	12′04.63″	29′54.27″	11′18.14″	30′43.49″	4,788	10.6
AF5X14231001	–	SW	3.1414	06′55.93″	17′05.28″	06′03.73″	15′43.83″	4,745	6.8
AF5X14231002	–	S	12.0400	08′04.19″	14′48.58″	06′09.86″	14′48.84″	4,812	23.7
AF5X14231003	–	SE	6.8352	06′46.16″	12′34.39″	06′02.56″	14′15.90″	4,875	34.6
AF5X14231004	–	E	4.5936	07′36.03″	22′58.02″	07′41.30″	24′30.89″	4,846	3.9
AF5X14231005	–	S	2.1312	08′51.36″	24′40.09″	08′12.08″	24′39.36″	4,849	10.1
AF5X14231006	–	NE	4.3370	13′29.40″	29′45.80″	14′03.70″	31′12.53″	4,600	8.9
AF5X14231007	–	NE	3.8426	13′04.60″	31′02.92″	13′36.68″	31′56.50″	4,540	10.3

Glacier retreat (m) and annual rates (m/year) computed from Landsat MSS and ASTER imagery. Glacier parameters were extracted from ASTER imagery

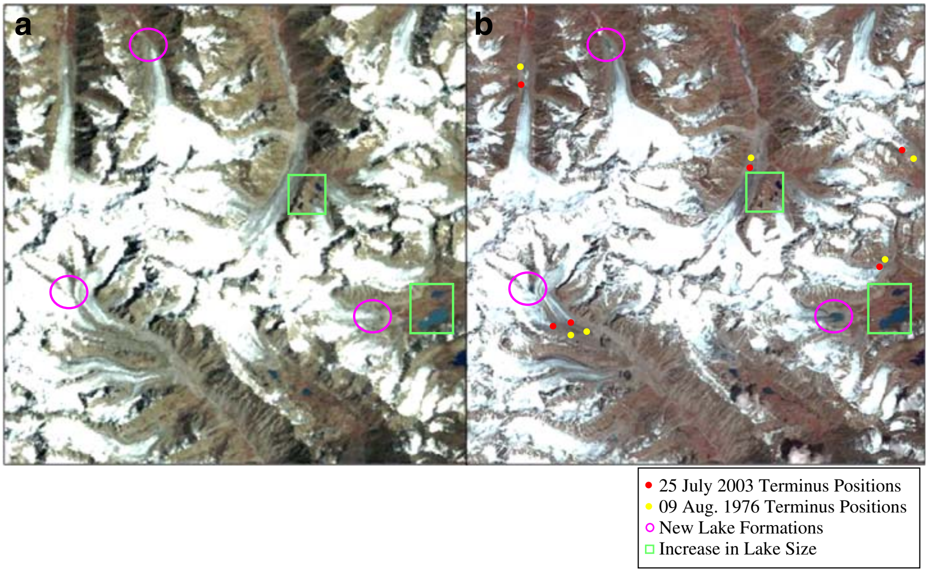

Fig. 3 Examples of glacier retreat, new lake formation and increase in lake size as observed in **a** 1976 MSS and **b** 2003 ASTER satellite imagery in the Wakhan Pamir

downwasting. For example, AF5X14231004 and West Little Ali Su, have significantly downwasted. The terminus regions of these glaciers are entrenched within a higher altitude, lateral and end moraine. Glacier geomorphological patterns provide strong evidence that apparent downwasting is a major part of the glacier mass loss in this region, rather than strict terminus recession. Paul et al. (2007) suggested that frontal glacier recession is often coupled to a lateral glacier thinning of a similar magnitude, although some glaciers in the region do not appear to be downwasting.

6 Surface hydrology

The process of formation and enlargement of glacier lakes is closely associated with downwasting and deglaciation. Multi-temporal image analysis indicated significant changes in the surface area of supraglacial, proglacial and valley lakes over the 27-year period. In particular, the creation of new high-altitude lakes is indicative of melting ice and snow due to warmer temperatures. Although we do not have climate station data to support this causation hypothesis, Khromova et al. (2006) found higher summer temperatures in the Eastern Pamir just north of our study area. Several high-altitude lakes formed on glacier AF5X14221005 and on the detached tributary of Northern Issik Glacier. The supraglacial lake (glacier AF5X14221005) is located in the accumulation zone at ~5,350 m. Conversely, the lake associated with the detached tributary of Northern Issik Glacier is a 43,900 m^2 proglacial ice-dam at ~5,040 m. Such impoundments are formed when melt water occupies the void left behind by retreating and downwasting glaciers, which are structurally weak and unstable. In addition, four new supraglacial lakes can also be observed on Ptukh Glacier. These supraglacial lakes are elongated and did not exist in 1976.

Detailed analysis of the sampled glaciers indicates that there are many more new proglacial lakes than supraglacial lakes. Frequency analysis reveals a total of 69 lakes with ten supraglacial and 59 proglacial. For example, there are six new proglacial lakes associated with West and East Little Ali Su glaciers, including a moraine-dammed lake with an area of 41,200 m^2 associated with the western glacier. Such unstable moraine-dammed proglacial lakes are common in the Himalaya region (Haritashya et al. 2006). Ptukh Glacier exhibits several supraglacial lakes, five proglacial lakes, and valley lakes, that have increased in area since 1976. One of the lakes has increased as much as 46,600 m^2 during this period. Similarly, proglacial lakes associated with AF5X14220100 and AF5X14230076 glacier have increased by 36,400 and 166,600 m^2, respectively (Fig. 3). Many more supraglacial lakes exist on other glaciers in the region, although these glaciers were not sampled.

In summary, the melting of snow and ice has resulted in new supraglacial, proglacial, and valley lakes down basin valleys that have increased in planimetric area. This is a general trend that we would expect given our estimates of glacier recession and geomorphological evidence of apparent downwasting.

7 Discussion

Our change-detection results and satellite observations are some of the first reported findings related to glacier fluctuations in the Wakhan Pamir. The data represent baseline information that has been included in the GLIMS database. Remote sensing investigations of glaciers are inherently limited by the quality of the imagery as defined by date of acquisition in relation to environmental variables (i.e. snow cover, atmospheric conditions, shadows). Consequently, we sampled all the glaciers that could be assessed in all the multi-temporal scenes, and believe that we have a quite reasonable representation in terms of glacier orientation, size and altitude.

Our image time-series analysis indicates apparent glacier downwasting and recession, and an increase in the frequency of large proglacial lakes. It is more difficult to ascertain changes in supraglacial lakes as they are smaller, and MSS data exhibits relatively coarse spatial resolution compared to ASTER. Although terminus positions prior to 1976 for these glaciers do not exist, we find strong spectral and morphological evidence of glacier forefields in the imagery that clearly reveal recession had occurred before 1976. Most glaciers exhibit a large forefield of deposited moraine caused by apparent downwasting and recession. Given that we do not have any dates to correspond with the furthest extent of ice that is well demarcated in the imagery, we cannot determine if the rate of recession has intensified over time; something we might expect given our climate simulation results. Our results, however, generally correspond to results from similar studies carried out in the Eastern Pamir (e.g., Khromova et al. 2006; Aizen et al. 2006), and with global results that indicate a general downwasting pattern (Paul et al. 2004). There also appears to be a relationship between glacier size and retreat rate. Larger glaciers have retreated more than the smaller one in the region. But just like glaciers in the Tien Shan, further north of the study area, no significant difference was noticed in the retreat of glaciers with different orientations (Solomina et al. 2004).

Our observations of apparent glacier downwasting and the evolution of proglacial lakes support climate-simulation results of higher temperatures and increased melting. The presence of new supraglacial and proglacial lakes caused by ablation produces a positive feedback which can intensify the ablation process. The temperatures of the water in these lakes are expected to get warmer through time, and this will facilitate further melting as lakes grow in size. For example, glaciers AF5X14221001 and AF5X14230076 exhibit features commonly referred to as thermokarst, which is caused by differential ablation due to lakes and thin debris cover. Furthermore, differential ablation and downwasting will cause new rock outcrops to exhume through the ice (e.g., Western Ali Su and Tila Bey). The outcrop islands intensify ablation and downwasting as they exhibit relatively low albedo and radiate thermal energy (Paul et al. 2007). Our study also reveals that most of the more extensively retreating glaciers results in greater number of supraglacial and proglacial lake formation.

8 Conclusion

Climate simulations and space-based observations on glacier fluctuations in the Wakhan Corridor indicate that these alpine glaciers are downwasting and retreating similarly to the glaciers observed in the eastern Pamir. Many larger glaciers exhibit higher retreat rates than smaller glaciers, although no systematic relationship between retreat rate, terminus altitude and glacier type was found. Furthermore, large glacier forefields exist for many glaciers, indicating that glacier recession had also occurred prior to 1976. These results also correspond to an increase in the frequency and size of proglacial and valley-basin lakes that have resulted from the melting of snow and ice in this region. Conversely, we find that changes in snow-line altitudes have been minimal, although we acknowledge that we have not systematically accounted for seasonal variations in snow line. On the other hand, because the Wakhan Corridor is directly adjacent to Pakistan and the Karakoram Himalaya where other climatic anomalies have also been detected recently (Archer and Fowler 2004; Hewitt 2005), it is plausible that increased summer precipitation from greater marine evaporation caused by climate warming and monsoonal enhancement explains the lower snowline altitudes we observed in summer imagery. Future monitoring of these glaciers and changes in surface hydrological conditions is warranted, as well as assessment of other regions in Afghanistan to ascertain the spatial pattern of glacier fluctuations in the Hindu Kush.

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