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On the Relationship between Local Topography and Small Glacier Change under Climatic Warming on Mt. Bogda, Eastern Tian Shan, China

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ABSTRACT: Glacial features in the geological record provide essential clues about past behavior of climate. Of the numerous physical systems on earth, glaciers are one of most responsive to climate change, especially small glaciers, their direct marginal response taking only a few years or decades to be expressed. Accelerating recession of modern glaciers raises the issue of the climate's impact on water runoff. Data based on topographic maps and Advanced Spaceborne Thermal Emission and Radiometer (ASTER) imagery show the trends that are highly variable over time and within the region. An analysis of the local topographic settings of very small (<0.5 km^2) glaciers was conducted to investigate their influence on recent changes in these glaciers. Among 137 glaciers, 12 disappeared completely. The study reveals that glaciers situated in favorable locations had tiny relative area reduction, while those in less favorable settings generally had large area loss or even disappeared. It is suggested that most of the small glaciers studied have retreated as far as they are likely to under the climatic conditions of the late 20th century. Undoubtedly, the strong retreating of small glaciers exerts adverse effects on the hydrologic cycle and local socioeconomic development.

KEY WORDS: glacier change, climatic warming, topography, Mt. Bogda, remote-sensing.

INTRODUCTION

Mountain topography reveals that about 26% of the world's population resides within mountains or in the foothills of mountains (Meybeck et al., 2001), and 40% of global population lives in the watersheds of rivers originating in various mountains of the world (Beniston, 2006). Alpine glaciers are excellent reservoirs that collect solid precipitation in winter and release those collections as melt water in summer and thus moderate variations in runoff and supply reliable water during drought periods. Alpine mountains provide subsistence to populations downstream. However,

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glaciers can experience major mass loss from trends in temperature, precipitation, and cloud cover or solar radiation (Shi et al., 2007; Yao et al., 2004; Alley et al., 2003). Small glaciers, due to high sensitivity and shorter response time to climate variance, are viewed as outstanding indicators of ongoing climatic changes. The retreat of mountain glaciers could have direct consequences for humanity. Major glacier recession, accompanied by marked changes in the glacial runoff, has led to frequent glacier-related natural hazards (Huss et al., 2007; Brázdil et al., 2006; Kääb et al., 2005; Jiang and hu, 2004; Huggel et al., 2003), ecological response (Chen et al., 2005; Hu et al., 2001; Engstrom et al., 2000; Fastie, 1995), and even dangerous living conditions (e.g., debris flows and water crisis) for human beings. Disappearing glaciers have a significant impact on mountain hydrology and leave new terrain for plant colonization. Consequently, the extent of glacier recession and its impact on local surroundings needs to be clearly understood.

Previous studies of glacier area changes within Tian Shan (Narama et al., 2010; Kutuzov and Shahgedanova, 2009) or worldwide (Paul et al., 2004a; Hoelzle et al., 2003) showed that small glaciers suffer greater reduction in area than larger glaciers do (Racoviteanu et al., 2008; Paul et al., 2004a). It is suggested that small glaciers are most affected by increasing summer air temperature and changing precipitation (Granshaw and Fountain, 2006; Kääb et al., 2002) or by the influence of change in solar radiation on mass balance (Huss et al., 2009). However, there is a dilemma in the substantial variability of areal change of small glaciers, ranging from vanished completely to advanced slightly when subjected to the same regional climate conditions during recent decades. Here, we study the glaciers on Mt. Bogda, where 77% of the 469 glaciers are less than 0.5 km^2, to understand the causes of apparent differences in behavior of these small glaciers. This study examines recent conditions on Bogda and attempts to shed light on the effect of topographic settings on small glaciers.

STUDY AREA

The study area is located in the eastern Tian Shan Mountains (43º10'N–44º5'N, 87º40'E–91º35'E), about 90 km east of Urumqi, where melting glacier water exerts a profound influence on water resources for this region (Fig. 1). The mountain is 330 km long with an area of 20 000 km^2. The highest peak, Bogda Peak, is 5 445 m high and has large glaciers concentrated around it. There are also two other high summits, at 5 278 and 5 213 m, within 3 km. This glaciated area is scattered with hanging glaciers, cirque glaciers, small valley glaciers, and ice caps. The western section of Mt. Bogda rises between Caiwopu-Dabancheng basin to the south and Junggar basin to the north. The

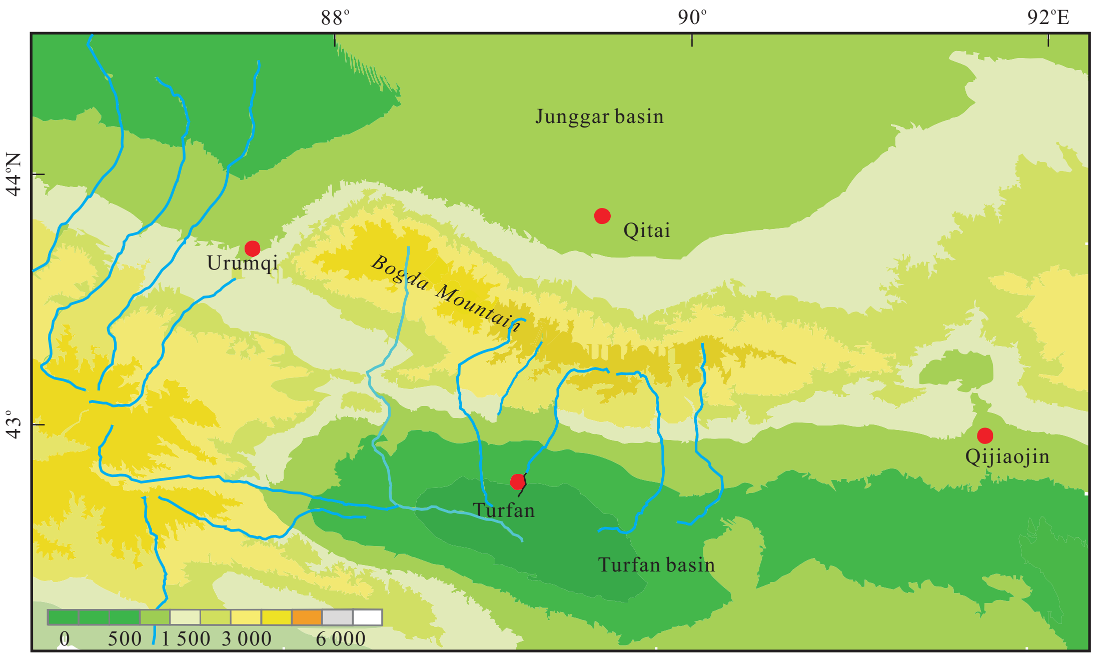

Figure 1. Location of Mt. Bogda together with the meteorological stations (represented by red circles).

northern slope descends in a steep and short morphology, where glacier size is limited by this topography, while the southern side extends further with a less steep slope, which is more suitable for glacier development. With altitude decreasing from west to east, smaller glaciers tend to develop on the eastern section of the mountain. On the southern side of Mt. Bogda, melting water is an important resource for supplying the Karez, which nourishes the oasis of Turfan basin, the lowest intermontane basin of the Tian Shan Mountain system (-155 m a.s.l. at its lowest point). Moreover, it is a reliable supplier to Caiwopu Lake, the main fresh water provider for the city of Urumqi. The melting water of Alpine glaciers is very important for the sustenance of these oases and for human existence.

There is a distinct climatic difference between the southern and northern sides of Mt. Bogda. High Mt. Bogda blocks moisture sources coming from the northwest and moving south, thus determining local climatic conditions. Junggar basin, to the north, is relatively humid, whereas the Turfan basin, to the south, tends to be fairly arid with high air temperatures (Wu et al., 1983). The arid Turfan basin depends largely on fluvial water originating from abundant Alpine precipitation and glacier mass loss. The basin is in the rain shadow of westerly flows and is famous for its higher evaporation and lower annual precipitation. The mean annual precipitation in Toksun County, for example, is only 8.4 mm, while the mean annual evaporation reaches 3 171 mm. Under the westerly air mass, this region is mainly influenced by the summer precipitation around Mt. Bogda. However, high evaporation in the southern periphery means that the precipitation cannot compensate for high evaporation losses.

METHOD AND DATA

Data Sources

Changes in Mt. Bogda glaciers, in general, have been underreported, largely because satellite images are affected by snow cover, and there is an absence of long-term systematic glacier observation. Although there were systematic field-based measurements for several glaciers in 1981 by a combined Chinese-Japanese investigation, the survey was limited primarily to the physical and chemical characteristics of the glaciers, with little attention to changes in area (Zhang, 1982). The current study uses topographic map information from 1962, remote sensing data from 2006, and additional field investigation in 2009 to provide information for correctly mapping the area of glaciers in this region.

The outlines and lengths of glaciers were mapped in 1962 based on 1 : 50 000 scale topographic maps and in 2006 using an Advanced Spaceborne Thermal Emission and Radiometer (ASTER) scene with a resolution of 15 m. The image was obtained for cloud-free conditions, making it immune to potential error, and at the end of the ablative period when snow cover was minimal, to avoid perturbation in delineating the glacier boundary. Another important factor in determining glacier outlines is debris cover and the lateral moraines around the ice tongue. Field investigation found that debris was not extensive in the area, and most glacier surfaces were clean. Excellent images ensured clear glacier boundaries, minimizing uncertainty.

The ASTER images were mapped glacier by glacier by manual interpretation. Data assessments conducted under GLIMS framework have confirmed that artificial interpretation remains the best tool for extracting higher-level information from satellite imagery for glaciers (Raup et al., 2007a), especially when glaciers are covered by debris (Raup et al., 2007b). The image was then orthorectified using methodologies described by Paul et al. (2004a, b) and PCI Geomatica 9.1 Orthoengine software (Kutuzov and Shahgedanova, 2009; Svoboda and Paul, 2009). A digital elevation model (DEM) with 25 m grid spacing, created by interpolating contour lines from topographic maps based on 1962 aerial photography, was used to derive elevation data for glaciers. Thirty ground control points (GCPs) from the image were selected (using the geometric correction tool available in ERDAS Imagine 9.0) to match the topographic maps with the root mean square error (RMSE) value limited to below 0.5 pixels.

Topographic Analysis

The glacier mass balance and runoff changes in Tian Shan are mainly controlled by summer temperature and less associated with precipitation increase (Ye et al., 2005). This control factor may be closely related to the receipt of direct solar radiation. Surrounding topography is the basic control factor on the receipt of solar energy by valley glaciers and has the greater influence on ice extent during times of warmer climate (López-Moreno et al., 2006). Shading by the surrounding terrain, as well as slope and aspect variations over the glacier surface itself, will affect the amount of direct solar radiation received. Many studies have emphasized the importance of topography in controlling direct solar radiation receipts. Arnold et al. (2006) show that shading reduces direct solar radiation receipts by 6%, while slope and aspect reduce radiation by 0.3% for the Midre Lovénbreen Glacier, Svalbard, Norway. Klok and Oerlemans (2002) suggest that shading reduces radiation receipts by 10% and slope and aspect by 9% for Morteratschgletscher, Switzerland. Obviously, the small Alpine glaciers are seriously affected by their settings, which play an important role in radiation receipts. However, large glaciers extend their snouts into lower locations and hence are less affected by shading caused by the surrounding topography. Therefore, it is important to consider small glaciers when assessing regional glacier changes.

Although mountains differ considerably from one region to another, one common characteristic is the complexity of their topography and the particular microclimate that imposes on local glaciers. Topographic features, slope, aspect, and exposure of the surface to climatic elements, play key roles in determining local microclimates. These factors tend to govern the development of mountain glaciers, as well as precipitation, which is the main input to glaciers. Precipitation in a mountain region is observed to increase with height. Generally, the windward-facing slopes of the mountains receive more precipitation, while the lee side is essentially dry. This leads to differences in mass accumulation between the various slopes and also in ablation caused by solar radiation. It is necessary to enhance our understanding of the role of mountains in supporting the valleys and plains below and to highlight some of the unique atmospheric features associated with regions of complex topography in determining glacier changes.

Indicators to evaluate the effects of climatic warming on small glaciers throughout the mountains were derived using shapefile polygons together with the DEM, generated from topographic maps. The glacier area (A, km^2) and length (L, m) in 1962 and 2006 were derived directly from the polygons, and only glaciers with initial surface area smaller than 0.5 km^2 were included in our investigation. The maximum and minimum elevation (Z, m) as well as the average slope (α, °) and aspect (ω, °) of each glacier in 1962 were also determined from the DEM, and those glaciers were matched with the images of Google Earth in order to avoid great error. Some glaciers that existed in 1962 were not found in satellite images in 2006, nor were they found through Google Earth. Thus, we maintain that those small glaciers had vanished completely. Individual glacier area change (C, %) is calculated by the ratio of latest area subtracting former area to its former area. The statistical information of the various topographic parameters is listed in Table 1, and glaciers that disappeared are distinguished from others. Generally, small glaciers located in higher locations experience cooler microclimates, where surface slope and aspect affect exposure, duration, and

Table 1 Summary of topographic sectors for 137 glaciers with initial area <0.5 km^2

Topographic parameter	Glaciers in net area decrease (n=122) or area increase (n=3)				Glaciers that disappeared (n=12)			
	Mean	Std dev.	Max.	Min.	Mean	Std dev.	Max.	Min.
A (km^2)	0.201	0.127	0.499	0.018	0.085	0.044	0.166	0.026
L (m)	655.8	275.7	1 622.0	127.0	390.1	134.5	545.0	90.0
Z (m)	4 154	253	5 280	3 780	4 070	141	4 300	3 880
α (°)	29.6	7.0	47.0	5.3	27.3	7.4	40.4	17.7
ω (°)	116	83	-	-	154	91	-	-
C (%)	-37.9	23.5	27.0	-96.2	-100	0	-100	-100

intensity of sun exposure. These factors tend to govern the redistribution of solar energy as it is intercepted at the surface, as well as snow cover, which is sensitive to surface slope.

RESULTS AND DISCUSSION

Area Change during 1962–2006

During the period of 1962–2006, all glaciers in Mt. Bogda have shrunk by 21.6% of their former value from 144.1 to 112.9 km^2. Strong relative reduction highly tends to smaller glacier (Fig. 2a), and 137 investigated glaciers in class of <0.5 km^2 contributed 10.0 km^2 to total area loss or reduced by 38.5% of their initial area. Glacier in different sizes suffers distinct area loss on condition of climatic warming, according to the glacier size class (0.01–0.1, 0.1–0.5, 0.5–1, 1–5, and >5 km^2). Apart from short response time to climate warming, behavior of small glacier change expressed high variability, which may attribute to micro-climate conditions or complicated topographic settings (Fig. 2b). In the sample, 12 small glaciers totally disappeared, and 3 glaciers advanced partly because of glacier surging. Thus, the large quantity of small glaciers will affect the value of relative area change in regional scale. Moreover, the results show a shift towards fewer and smaller glaciers over this period due to net area loss. It is suggested that more glaciers will become smaller and are likely to vanish in the near future.

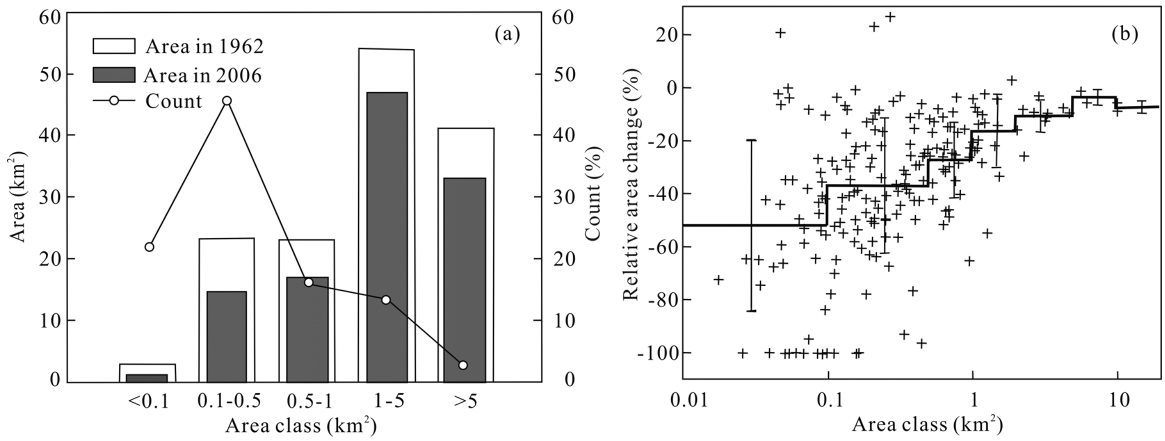

Figure 2. (a) Area and count distribution over the period of 1962–2006, according to size class (<0.1, 0.1–0.5, 0.5–1, 1–5, and >5 km^2), and (b) relationship between glacier area and relative area change (%).

Regional Climatic Conditions

Variation in the actual position of glacier margins reflects mass balance between mass influx and ablation and is largely controlled by summer temperatures (Ye et al., 2005; Vincent et al., 2004). In general, during climate warming, increased ablation overwhelms mass input, thus forcing glacier margins to retreat, while during climate cooling the margins tend to extend. Tracing fluctuations in glacier area and terminus, therefore, is the best way to demonstrate the relationship between climate change and glaciers. Although the meteorological data derived from four sites at lower elevations around Mt. Bogda (Fig. 1) may not be truly representative of conditions near the glaciers, they do provide a sense of recent climatic variability within the region. Due to obstruction of the airstream by the high mountain, great differences exist between the southern periphery and the northern periphery. Climatic conditions around the mountain are represented by yearly mean air temperature and precipitation data from the weather stations for 1959–2002. There has been a definite tendency for air temperatures to increase since the 1990s. Among the four stations, temperature increased at a rate of 0.18–0.53 ℃·$10a^{-1}$ and higher for Qijiaojin and Turfan (Table 2). Another factor that adversely affects glacier ablation is precipitation, which showed a slight increase, 0.8 mm·$10a^{-1}$ for Turfan (south) and 2.1 mm·$10a^{-1}$ for Qijiaojin (east) but far less than for the other stations of 14 to 47 mm·$10a^{-1}$. This suggests that glaciers on southern and eastern sides of mountains are more unfavorable for the existence of glaciers.

The limitation in our analysis is that stations are at low elevation (<1 000 m a.s.l.) and that no information about the climate and its change is available for high mountains. The studies of Urumqi Glacier No. 1 (UG1) indicated that the retreat was mainly controlled by air temperature increase (Li et al., 2007; Ye et al., 2005). It has to be noted that the data of Daxigou Meteorological Station (43º06'N, 86º50'E, 3 539 m a.s.l., about 2 km downstream of the UG1) resulted in a similar trend of the average temperature increase. The temperature increment in the mountains based on six stations ≥1 943 m a.s.l. is also documented by Bolch (2007) and suggested that the glacier retreat in northern Tian Shan correlates well with increased air temperatures. Investigations among Tian Shan suggested that marked increase of air temperature is a driving factor for regional glacial recession.

On the periphery of Mt. Bogda, the main factor determining the glacier regime is the interaction between temperature and precipitation. Although it is difficult to clearly understand the relationship between climatic forces and glacier response, the common sense is that declining glaciers are caused primarily by sensitivity to climate change (Anderson et al., 2010; Oerlemans and Reichert, 2000). The increase was not continuous and there were also phases of cooling, but the tendency toward increasing temperature, especially after 1990, may be evidence that mountain glaciers experienced climate warming in this area (Fig. 3). Also, precipitation increased slightly for the northern and western stations, Qitai and Urumqi, while for the eastern station, Qijiaojin, precipitation data show a decline in the late 1990s. The precipitation and temperature gradients around the mountains may also explain why small glaciers predominate in the eastern section.

Table 2 Location of meteorological station and basic information of precipitation and temperature over 1959–2002

Station	Location	Elevation (m)	MAAT (℃)	Increase rate (℃·$10a^{-1}$)	MAP (mm)	Increase rate (mm·$10a^{-1}$)
Qitai	44º01'N, 89º34'E	793.5	5.2	0.25	193.1	24.8
Urumqi	43º47'N, 87º39'E	935	7.1	0.18	262.6	47.3
Turfan	42º56'N, 89º12'E	345	14.4	0.42	16.3	0.8
Qijiaojin	43º13'N, 91º44'E	721.4	9.7	0.53	37.6	2.1

Local Topographic Settings

Glaciers that decreased in area or disappeared in particular regions were mainly influenced by local temperature and precipitation. Glacier distribution is also affected by non-climatic factors, such as aspect, elevation, surface slope, and even size. These influencing factors may be attributed to the effect of solar radiation, which has been shown to be the largest component of glacier surface energy balance affecting ablation for mountain glaciers (Oerlemans and Kanp, 1998). Glacier recession resulting from temperature increase or solar radiation is spatially homogenous with respect to different aspects and their surrounding topography.

The aspect values denoted as W, NW, N, NE, E, SE, S, and SW are inappropriate to use in ordinary linear statistics; therefore, the direction of the vector is converted to degrees, moving counterclockwise (0º, 45º, 90º, 135º, 180º, 225º, 270º, and 315º) (Fig. 4a). Glaciers with a northerly aspect (45º–135º) are clearly the most common, but many glaciers also have aspects within the range of 180º to 360º. Glaciers faced south are prone to area loss. This indicates that sites facing toward the sun in mid-afternoon are favorable for glacier melting, the tendency partly due to solar radiation and maximum air temperature (Evans, 2006). The intuitive thought is that glaciers facing north are more sheltered from sunlight and suffer gentle ice loss. Figure 4b shows a large quantity of small glaciers located in the altitudes of 3 800 to 4 500 m a.s.l., with relative area shrinkage between -100% and 27%. There is a slight tendency for greater recession towards the lower locations. Figures 4c and 4d indicate that glaciers' mean surface slope is commonly within the range of 19º and 40º with mean value of 29.4º, and the slope value tends to be smaller with increasing size. Most glaciers that slope smaller than the mean value are very small glaciers (Fig. 4c). The statistic results show

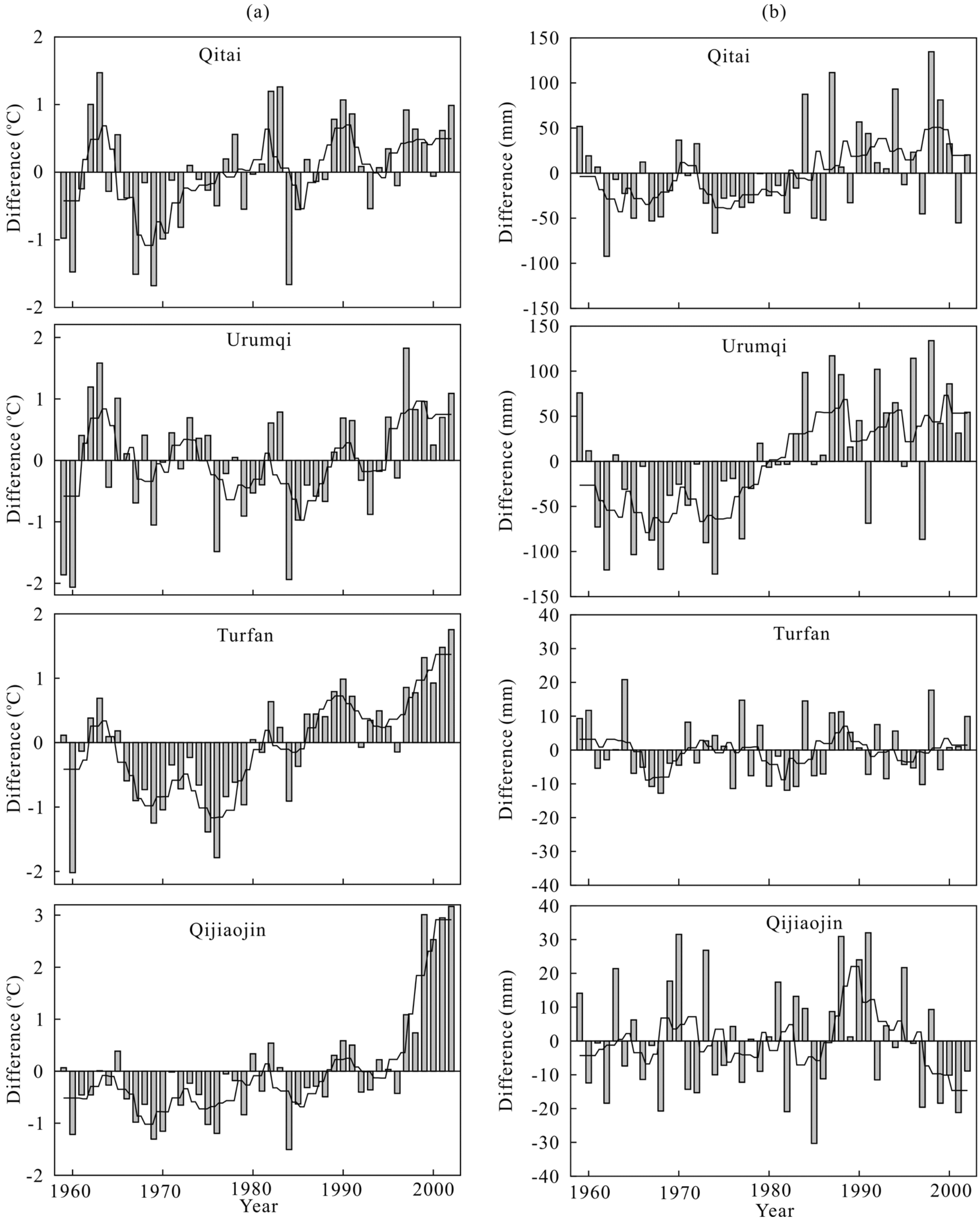

Figure 3. Time series of temperature deviation (a) and precipitation deviation (b) from the climate norm period 1959–2002 of selected climate stations. The black thick lines represent 2-year moving average.

that 68 glaciers situated below relatively less steep slopes (29.4º) with mean size of 0.23 km^2 reduced their area by 40.6% and 69 glaciers situated above mean slope with mean size of 0.15 km^2 reduced their area by 35.3%. Small cirque glaciers may retreat into classic cirque basins. Some of these basins may be strongly illuminated by the sun or reflected radiation, whereas, in others, nearby peaks and ridges may produce strong shadows. The sun-sheltered basins can explain why some glaciers are in modest recession.

Table 3 provides detailed information of interrelationships between the variables for individual glaciers. The matrix of correlation coefficients expresses the simple measure in related indices. Although the results are limited by sample size, data quality, and other parameters, they provide light on the subject of glacier change. Many of the parameters are significantly correlated with each other, but all factors contribute integrally to glacier ablation.

North-facing glaciers are in a much more favorable position than glaciers facing south (Fig. 4a). The differences of shade and radiation incidence in different aspects affect glacier mass balance in accumulation areas. It is particularly important in mid-latitudes (30º–70º) (Evans, 2006). The direction glaciers face is closely related to their elevations, because glaciers facing south receive more direct solar radiation and thus recede into higher locations. It is suggested that glaciers situated at relatively low elevations are commonly glaciers facing north. Slopes oriented towards the south receive more energy per unit area and therefore experience larger thermal amplitude than other orientations. Differential absorption and distribution of energy at the surface of glaciers facing different ways lead to different atmospheric responses.

Altitude certainly impacts mountain climates in

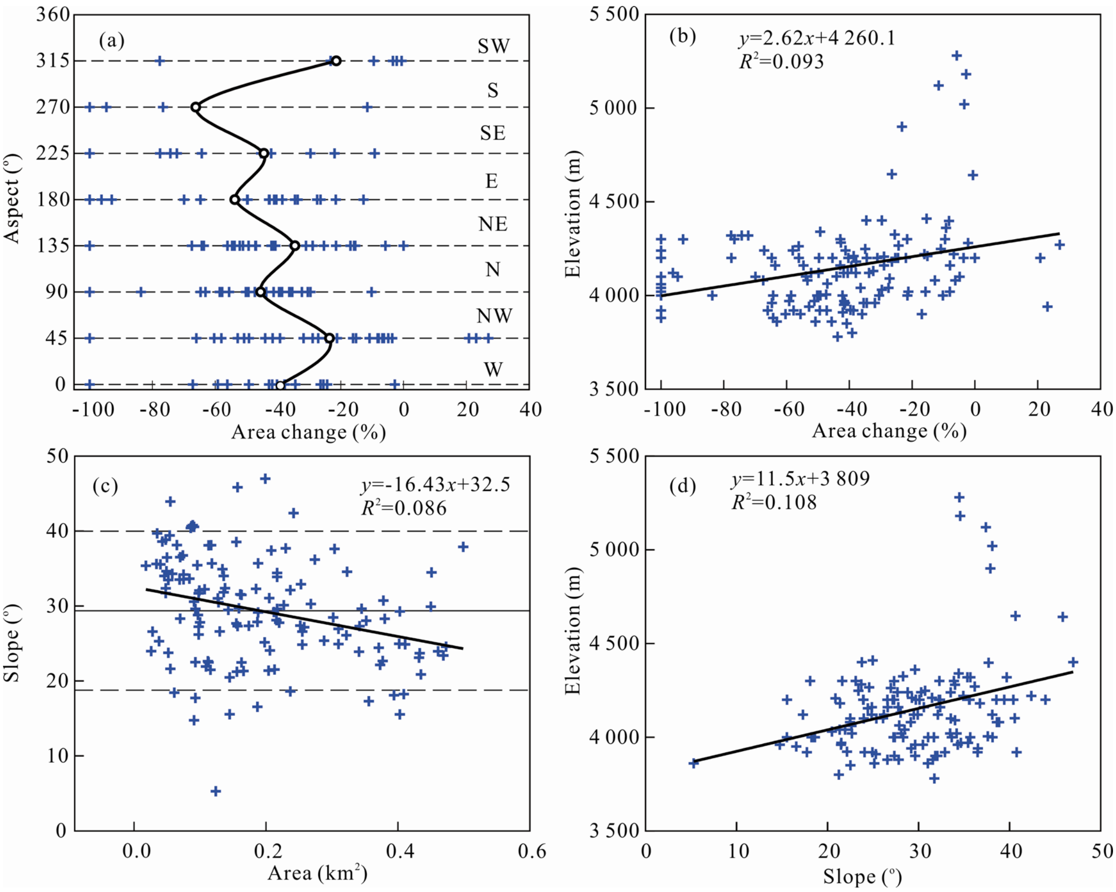

Figure 4. Scatter plots showing relationships between (a) aspect versus area change, and the red circles represent the mean area change in each aspect class, (b) elevation versus area change, (c) slope versus area, and (d) elevation versus slope.

Table 3 Pearson's correlation matrix of topographic and geometric indices

	Area	Length	Elevation	Slope	Aspect	Area change
A (km^2)	1.00					
L (m)	0.77	1.00				
Elevation (m)	0.28	0.29	1.00			
Slope (º)	-0.29	-0.24	0.33	1.00		
Aspect (º)	-0.04	-0.05	0.25	0.02	1.00	
Area change (%)	0.26	0.30	0.31	0.18	-0.18	1.00

Underline values indicate significance at the 95% confidence level.

terms of atmospheric density, pressure, and temperature, which decrease with height in the troposphere. The high-elevation glaciers may retain snow cover later in summer due to higher snow accumulation and reduced melt rates, which maintains a relatively high albedo and limits the net shortwave radiation receipt, while glaciers situated at relatively lower elevations are sheltered to a greater extent from direct solar radiation, and this tends to create a local microclimate that is cooler and more favorable for ice preservation (Debeer and Sharp, 2009). The topographic settings of small glaciers indicate that ablation rates for these glaciers at a given elevation are likely much less than for the larger and more exposed glaciers at equivalent elevations (Fig. 4b).

Glacier area and length are key factors in determining their shape and shrinkage. The above correlation analyses provide significant evidence that glacier size is affected more by local topographic variables than is glacier aspect (Table 3). Generally, glacier area (*A*) and length (*L*) are synchronously controlled by their topographic settings. Figure 4c provides an insight into relationship between slope of individual glaciers (α) and their area (*A*). Larger glaciers have multiple sources and low gradients, blurring and reducing the effects of slope aspect. The elongated glacier is prone to greater recession due to more edge system exposure under direct solar radiation. The extension of glacier terminuses in lower elevations may be sensitive to the recent air temperature increases.

Correlation analysis shows that mean surface slope relates with other parameters. It is negatively related with glacier area (*A*) and length (*L*) while positively correlating with relative area change (*C*) and elevation (*Z*) (Table 3). These interrelationships suggest that larger glaciers are generally less steep and tend to have more extensive contributing areas at higher elevations (Fig. 4d). The westerly circulation influencing the region leaves more precipitation on the windward (northern) slope. Thus, the incidence of solar radiation becomes the dominant influence on the aspect of local glaciers.

Potential Impacts

Impacts on water resources

The widely held concern related to future glacier recession is water supply. Mountain regions produce regional-scale concentrations of precipitation on upwind slopes and rain-shadow effects in the lee of mountains. Mountain glaciers provide an important reliable water supply during drought summer season. Thus, glaciers are potentially significant water reservoirs that buffer stream discharge and regulate the river runoff of seasonal melt water. If intense precipitation meets with strong glacier melting in the warmer season, they will produce a glacier lake outburst flood. Thus, understanding how much of surface water originates from glacial melt is important for planning purposes, especially in the context of rapidly retreating glaciers. Summer temperature is a significant element influencing runoff by controlling the ablation in highly glaciated Alpine basins, and the change of glacier cover is the key factor that results in runoff change (Chen and Ohmura, 1990). It is widely accepted that certain climatic changes are accompanied by negative effects, such as strong glacier retreating and serious water shortage. One of the most imposing problems on Mt. Bogda is related just to water resources, with the increasing shortage of water caused by desertification and the rapid melting of glaciers in the mountains. Rapid glacier retreat under climatic warming threatens the region with floods in the short run and with water shortage in the longer run. The evolution may aggravate a large number of problems, including the threat to food security and mountain populations being faced with significant social and economic hardships.

Strong glacier shrinkage was shown to greatly reduce water storage and thus water resources. Changing climate was characterized by changes in seasonal and annual precipitation, proportions of solid-to-liquid precipitation, and extreme events. Those factors influenced the magnitude of glacier melting or reduced the runoff of streams by reducing the volume in the long run. Glaciers significantly modify stream flow in quantity, variability, and timing by temporarily storing water as snow and ice in liquid form on different timescales. Under the climate warming, glacial runoff includes an initial increase and peak flows, and amplification in diurnal runoff oscillation, followed by significantly reduced runoff as the glaciers retreat. Given glacier retreat continues in the next decades, annual runoff from the highly glacierized drainage basins will show an increase that is due to the release of water from glacial storage and then drops below the current level after some decades (Huss et al., 2008).

For the lower glacierized drainage basins, runoff is mainly controlled by the variations of precipitation. Decrease in runoff could occur as a result of increase in evapotranspiration that outweighs increases in precipitation in spite of slightly precipitation increment of the mountain. The estimation conducted by Wang (1993) shows that about 21% of the glacial area will disappear in Northwest China if temperature increases by 1 to 1.3 ℃ and precipitation decreases by 60 to 80 mm. Our results expressing a relative area reduction of 21.6% of their former area coincide with the value. Most glaciers with an area less than 0.5 km^2 in Mt. Bogda are expected to disappear if temperature increases continue. Future glacier recession will seriously affect the eastern section of Mt. Bogda, where more small glaciers are distributed. The downstream population is mainly dependent on glacier fed water, such as in Turfan, where irrigation and other human activity mostly rely on the Karez, where water originates from glacier melt. Reduction in the number of Karez from more than 1 700 in 1962 to 1 108 in 2009, with water in only 278, may be more evidence of the negative effects of climate change (http://www.tlf.gov.cn/xwysym.jsp?urltype=news.NewsContentUrl&wbnewsid=38123&wbtreeid=305). The small size in eastern part of Mt. Bogda and their relatively short response time to climate fluctuation make them particularly vulnerable to ice supply.

Accurate estimation of changes in future runoff is difficult and needs more detailed observation parameters. The fact that melt water production is the strongest in hot and dry periods is due to the existence of Alpine glaciers. Future discharge is simulated by doubling the CO_2 scenario and a 50% reduction in glaciation in Tian Shan (Hagg et al., 2007) suggests higher risks of flood in summer turning into a runoff deficiency after a higher degree of deglaciation is reached. Projection of future discharge on Hindukush-Karakorum-Himalaya region conducted for 100% and 50% glacier scenarios generally shows an increase and a drastic decrease in water resources for 0% of glacier coverage (Akhtar et al., 2008). Increases in temperature and precipitation are shown for the 21st century, which means that additional water is expected to be released from glacier storage, thus modifying the current stream flow regime. It would also provide the region more melt water for economic promotion as well as more flooding problems in the future.

Impacts on ecological systems

The potential impact of glacier recession on mountain ecosystems is an increasingly important issue related to changes in Alpine environments caused by changes in climate. Further changes in global warming and local precipitation patterns could significantly alter the altitudinal ranges of important species and create additional environmental stress on already fragile mountain ecosystems. A plant's response to these climatic changes is a process of adaptation through a number of morphological and physiological adjustments, such as stunted growth forms and small leaves, lowering thermal requirements for basic life functions. Thus, change in distribution of vertical vegetation zones could strongly alter tree species' composition. Mt. Bogda has complete vertical landscape zones, including glacial and permanent snow belt (3 500 m), Alpine subglacial belt (3 200–3 500 m), Alpine meadow steppe belt (2 700–3 200 m), mountain forest belt (1 500–2 800 m), mountain desert-steppe belt (1 200–1 500 m), mountain desert belt, and desert belt (Wu et al., 1983). Altitudinal vegetation distribution has been seen as the characteristic of mountain environments. Changing climate and retreating glacier terminuses undoubtedly lead to vegetation moving up the mountain (Crocker and Major, 1955). A 3 ℃ change in temperature will lead to a 500 m change in altitude of mountain nature reserves (Peters and Darling, 1985). Measures should be taken to avoid desertification in the headwater areas, shrinkage of wetlands, deterioration of grasslands, and water pollution that might all be caused by those changes.

Impacts on socioeconomic systems

Mountain regions provide people with diverse industry to promote local economic growth and social progress. The specialty economy, such as tourism, agriculture, and pasture husbandry, together with hydropower, is closely dependent on the Alpine water resources. For example, the famous natural Heaven Lake, located in the upper stream of the Sangong River on Mt. Bogda, provides local government revenue of nearly ¥1 billion as well as hundreds of job opportunities. Moreover, excessive heat and unusual topographical features bring tourists to the Turfan distinct. The cultural relic in this region is the Karez, an underground irrigation system that is dependent on Alpine glacier melt water. This underground irrigation system, also called "underground Great Wall", attracts large numbers of tourists to this oasis in fire-land. The tourist industry is affected when scenic mountain glaciers shrink and waste away. With increasing temperatures and shortened periods of cooling, climate-related tourism, including winter skiing and summer journeys, will experience direct economic consequences.

Another substantial economic contribution to this area comes from agricultural production. Upland regions are characterized by altitudinal climatic gradients that can lead to rapid changes in agricultural potential over comparatively short horizontal distances. The upland crop production can be highly sensitive to variations in climate.

The hydrological cycle caused by global warming is linked to potential changes in runoff extremes. People in mountain regions or downstream highly depend on unregulated river systems and thus are particularly vulnerable to climate-driven hydrological change. Clearly, strong glacier melting from climate change, together with increased runoff in warmer seasons, provides more opportunity to generate power from existing hydroelectric stations. However, hydropower infrastructure planning needs to be considered. Hydropower resources are particularly important for the north side of the mountain.

CONCLUSION

Small glaciers on Mt. Bogda have experienced strong retreat and lost 38% of their 1962 area. Although the total reduced area of 137 glaciers is only 10.0 km^2, the great number and their impact on local environment is serious. Disappearing glaciers have a significant impact on mountain hydrology and leave new terrain for plant colonization. Glacier recession and disappearance also cause significant changes to the vegetation cycle of Alpine plant species. Climate warming poses a real threat to social and economic systems in the region. The reduction in Bogda glaciers has created water supply problems for downstream communities. The most significant aspect of glacier retreat may be intangible and intuitive evidence of broader environmental changes, but these are more difficult to measure. Investigating small glaciers that will soon be gone, compared with measuring large glaciers, can more closely reflect the present and near future states.

A quantified assessment of glacier shrinkage on Mt. Bogda reveals that great differences lie in those small glaciers. Under local climatic conditions, the distinct topographic attributes, such as surface slope, elevation, and aspect, tend to govern the redistribution of radiation receipt and thus determine, to a large extent, the existence of the glaciers. Moreover, precipitation is highly sensitive to the local site, such as height, windward-facing slopes, or lee side. There tends to be an overwhelming number of small north-facing glaciers both in number and in area cover. It is suggested that the northern slope is more favorable for glacier development. Therefore, the glacier change is interacted under these topographic vectors and determines their future evolution. Monitoring these small glaciers is more complicated than for larger glaciers with clearly defined ablation zones. However, the frequent existence of small glaciers in Alpine regions may be a valuable indicator of high-elevation climate.

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