Variations in Albedo on Dongkemadi Glacier in Tanggula Range on the Tibetan Plateau during 2002–2012 and Its Linkage with Mass Balance

Authors: Wu, Xuejiao, Wang, Ninglian, Lu, Anxin, Pu, Jianchen, Guo, Zhongming, et al.

Source: Arctic, Antarctic, and Alpine Research, 47(2) : 281-292

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/AAAR00C-13-307

Arctic, Antarctic, and Alpine Research, Vol. 47, No. 2, 2015, pp. 281–292

Variations in albedo on Dongkemadi Glacier in Tanggula Range on the Tibetan Plateau during 2002–2012 and its linkage with mass balance

Xuejiao Wu[1,2]
Ninglian Wang[1,5,6]
Anxin Lu[3]
Jianchen Pu[1]
Zhongming Guo[1,2] *and*
Huawei Zhang[4]

[1]State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, No. 320 Donggang West Road, Lanzhou, Gansu 730000, China
[2]University of Chinese Academy of Sciences, No.19A Yuquan Road, Beijing 100049, China
[3]Laboratory of Digital Earth Sciences, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, No.9 Dengzhuang South Road, Haidian District, Beijing 100094, China
[4]School of Tourism and Geographical Sciences, Yunnan Normal University, No.768 Juxian Street, Chenggong, Kunming 650092, China
[5]Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, No.16 Lincui Road, Chaoyang District, Beijing 100101, China
[6]Corresponding author: nlwang@lzb.ac.cn

Abstract

Albedo, which impacts the surface heat budget of a glacier, is a dominant factor governing snow and ice melt variability. We analyzed variations in albedo on the Dongkemadi Glacier (92°4.94′E, 33°05.88′N) using MODIS daily snow albedo products. The results show that the summer albedo over the accumulation zone and the ablation zone all presented a decreasing trend from 2002 to 2012, and both precipitation and summer temperature were critical factors that impacted variations in the albedo of the glacier. We linked the albedo variation with the measured mass balance of the glacier and found that 2006 and 2010 were high-melt years at the Dongkemadi Glacier, with lower albedo and a more negative mass balance. The area around the equilibrium line altitude (ELA) on the glacier was very sensitive to albedo feedback. The albedo change rate reached approximately −34% when the summer average temperature increased about 1 °C and the summer precipitation declined 94.5 mm. We built a linear model between the annual lowest albedo and the annual mass balance of the Xiao Dongkemadi Glacier, one branch of the Dongkemadi Glacier. This model was used to evaluate the annual mass balance of another branch of the Dongkemadi Glacier, the Da Dongkemadi Glacier. The mass balance of the Da Dongkemadi Glacier was significantly negative in 2006 (-768.7 mm w.e.) and 2010 (-696.9 mm w.e.). This work indicates that the glacier surface annual lowest albedo may be a reasonable proxy for evaluating the inter-annual variability of the mass balance of the glacier.

DOI: http://dx.doi.org/10.1657/AAAR00C-13-307

Introduction

Surface albedo is referred to as bihemispherical broadband albedo and is the ratio of the radiant flux reflected from a unit surface area into the whole hemisphere in relation to the incident radiant flux of hemispherical angular extent (Schaepman-Strub et al., 2006). The albedo of glaciers varies both temporally and spatially. It can range from more than 90% for fresh snow down to approximately 20% for dirty ice (Oerlemans and Knap, 1998). The variation in albedo on a glacier primarily depends on two aspects, the physical properties of snow and ice, and the solar radiation as affected by clouds (Kylling et al., 2000). Correctly measuring and predicting albedo is critical not only because solar radiation is a significant aspect of the surface heat budget, but also because the ice albedo feedback can amplify ongoing changes in the cover (Perovich and Polashenski, 2012). Thus, it is necessary to monitor variations of surface albedo on glaciers to understand cryospheric changes and climate feedback. Furthermore, albedo is an important parameter in climate models and in the energy balance models of glaciers or ice sheets. With the development of these models, spatial and temporal estimates of the albedo of ice and snow are required (Liang et al., 2005; Pedersen and Winther, 2005; Munneke et al., 2011).

Field measurements can provide reliable data for glacier albedo variation analysis. Usually, automatic weather stations (AWSs) installed at the glacier surface are used to monitor the temporal variation of albedo. Field measurements are invaluable but are difficult to acquire because glaciers or ice sheets are usually distributed in high-altitude or high-latitude regions. Another limitation of point field measurements is that they only capture the data in a point on the glacier surface, but the glacier surface is heterogeneous. In recent years, remote sensing has been shown to be a desirable and efficient way to detect the characteristics of glaciers, such as for monitoring snow cover (Immerzeel et al., 2009; Fassnacht et al., 2012), ice thickness (Kwok and Rothrock, 2009), and mass balance (Ramillien et al., 2006). Stroeve et al. (2001) provided temporally and spatially consistent estimates of the Greenland Ice Sheet albedo using the AVHRR Polar Pathfinder (APP) albedo data set; they analyzed albedo variation spanning 1981–1998. Jiang et al. (2010) investigated the spatiotemporal variation in albedo on the Qiyi Glacier in the Qilian Mountains of China, based on spectral pyranometers and data sets from an AWS. Tedesco et al.

(2011) analyzed the role of low albedo in the 2010 melting record in Greenland using remote-sensing data, surface observations, and output from a regional atmosphere model. Flanner et al. (2011) concluded that the albedo feedback from the Northern Hemisphere cryosphere falls between 0.3 and 1.1 W m^{-2} K^{-1}, using MODIS MCD43C3 data in conjunction with CMIP3 models.

Some researchers have deliberated linking glacier albedo and glacier annual mass balance. Greuell et al. (2007) estimated annual anomalies of the surface mass balance of glaciers on Svalbard, a Norwegian archipelago in the Arctic Ocean, for the period 2000–2005, by calculating the so-called ''satellite-derived mass balance'' from a time series of satellite-derived surface albedos. Historical mass balance gradients of glaciers were combined with MODIS-derived equilibrium line altitutdes (ELAs) to estimate annual mass change at the Columbia, Lillooet, and the Sittakanay ice fields in British Columbia, Canada (Shea et al., 2012). Dumont et al. (2012) processed one decade (2000–2009) of MODIS data to create a time series of albedo maps of the Saint Sorlin Glacier in the western Alps of France during the ablation season, and concluded that monitoring of the glacier surface albedo may provide a useful means to evaluate the inter-annual variability of the glacier mass balance.

In China, previous research primarily focused on monitoring variation in glacier albedo based on point field measurements. For example, based on AWS data, Yang et al. (2010) analyzed the temporal variation in albedo on the Rongbuk Glacier in the Himalaya Mountains over one year. Sun et al. (2012) analyzed the correlation of albedo variation and glacier melting in the accumulation zone of the Laohugou Glacier No. 12 in the western Qilian Mountains, China. However, to our knowledge, less research has been done concerning the spatial distribution and temporal variation of albedo on glaciers.

The goals of this study were, first, to assess the spatiotemporal variations in albedo on the Dongkemadi Glacier on the Tibetan Plateau based on remote sensing data and to analyze the impact factors and feedback mechanism of the albedo on that glacier. Second, we aimed to build a valid model between albedo and glacier mass balance based on the albedo feedback mechanism on the Xiao Dongkemadi Glacier. Finally, we wanted to produce a mass balance estimation of another branch of the Dongkemadi Glacier (Da Dongkemadi) based on the built model.

Study Site

The Dongkemadi River basin is a typical river basin of the headwaters of the Yangtze River on the Tibetan Plateau, where the elevation is over 5000 m a.s.l. The basin is a tributary at the upper reaches of the Buqu River near Tanggula Mountain Pass. There are 117 glaciers with a total area of 195.73 km^2 and volume of 14.4 km^3 in the Buqu River region (Pu et al., 1995). The Dongkemadi Glacier (92°4.94′E, 33°05.88′N) is located at the headwaters of the Dongkemadi River (Fig. 1) and is a subcontinental type of glacier. It is composed of the Da (Greater) Dongkemadi Glacier and the Xiao Dongkemadi Glacier, converging at the glacier terminus. The Da Dongkemadi Glacier's area is 14.63 km^2 with a length of 5.4 km. In 1993 the elevation of the terminus of the glacier was 5275 m and the ELA of the glacier was 5600 m (Pu and Yao, 1993). The Xiao Dongkemadi Glacier's area is 1.767 km^2 with a length of 2.8 km and an average width of 0.5–0.6 km. The summit and the terminus of the glacier are at elevations of 5926 m and 5380 m a.s.l., respectively, with a relative height difference of 546 m (Yao et al., 2012).

The Dongkemadi Glacier accumulates during the summer monsoon season. The melting period of the glaciers in the Tanggula Mountains is short, being only 21 days, with a daily average air temperature above 0 °C and a maximum air temperature of 3.5 °C (Pu et al., 1995). From AWS data observed near the equilibrium line (5600 m a.s.l.) on the glacier, the average annual air temperature and precipitation are –9.8 °C and 302 mm, respectively (Pu et al., 2008). With a gentle surface and without any avalanche or surface moraines, the glacier is an ideal place for mass balance study. The mass balance of the Xiao Dongkemadi Glacier has been monitored since 1989, with recording still ongoing.

Data and Methods

MODIS ALBEDO PRODUCTS AND PROCESSING

MOD10A1 daily products were retrieved from the Terra platform MODIS sensor from the National Aeronautics and Space Administration (NASA) taken from 5 March 2000, which is available from the National Snow and Ice Data Center (NSIDC). The product contains snow extent, snow albedo, fractional snow cover, and quality assessment data at 500 m resolution, gridded in a sinusoidal map projection. More frequent and higher spatial resolution albedo maps are provided by the product, which is suitable for cryospheric research. Validation efforts have shown that MOD10A1 albedo values are within 10% of in situ values in the Karasu Basin, Turkey (Tekeli et al., 2006). Comparisons with in situ observations at five AWSs in Greenland indicated an overall RMS (root mean square) error of 0.067 for the Terra instrument and an RMS error of 0.075 on Aqua. Stroeve et al. (2006) have suggested that MOD10A1 albedo products capture the natural seasonal cycle in albedo but exhibit significantly more temporal and spatial variability than recorded by ground observations. The products on the continental-type glaciers are also reasonably accurate, with an average error of less than 0.026 for albedo, and an RMS error less than 0.068 for albedo (Wang et al., 2011). In this study area, in situ observations had been taken in field work on 11 May 2011. Our open observation site was located at the end of the Dongkemadi Glacier, at 33°3.8′N, 92°4.7′E with an elevation of 5260 m. Albedo was measured by an albedometer (CMA11, Kipp & Zonen, Delft, Netherlands) with a wavelength range from 310 nm to 2800 nm. The absolute difference between MOD10A1 albedo (0.592) and in situ observation (0.638) was small (0.046) on 11 May 2011.

In this research, MOD10A1 daily albedo products were compiled over the Dongkemadi Glacier from March 2002 to October 2012. Only images in which the selected pixels were not cloudy were considered. About 215 images per year were selected over the period from April to October, covering the whole ablation period. In order to detect the variation of the albedo averaged over the whole glacier surface, only the data of pixels entirely within the glacier boundary were used, and potential mixed pixels on the side of the ablation zone were discarded to reduce biases. A total of 41 pixels (Fig. 2) were chosen for computing the average glacier albedo spatially.

The summer average albedo (from June to August) for the 11 years was calculated to detect spatiotemporal variation in albedo of the glacier during the ablation season. During the melt period, the glacier surface was generally comprised of bare ice

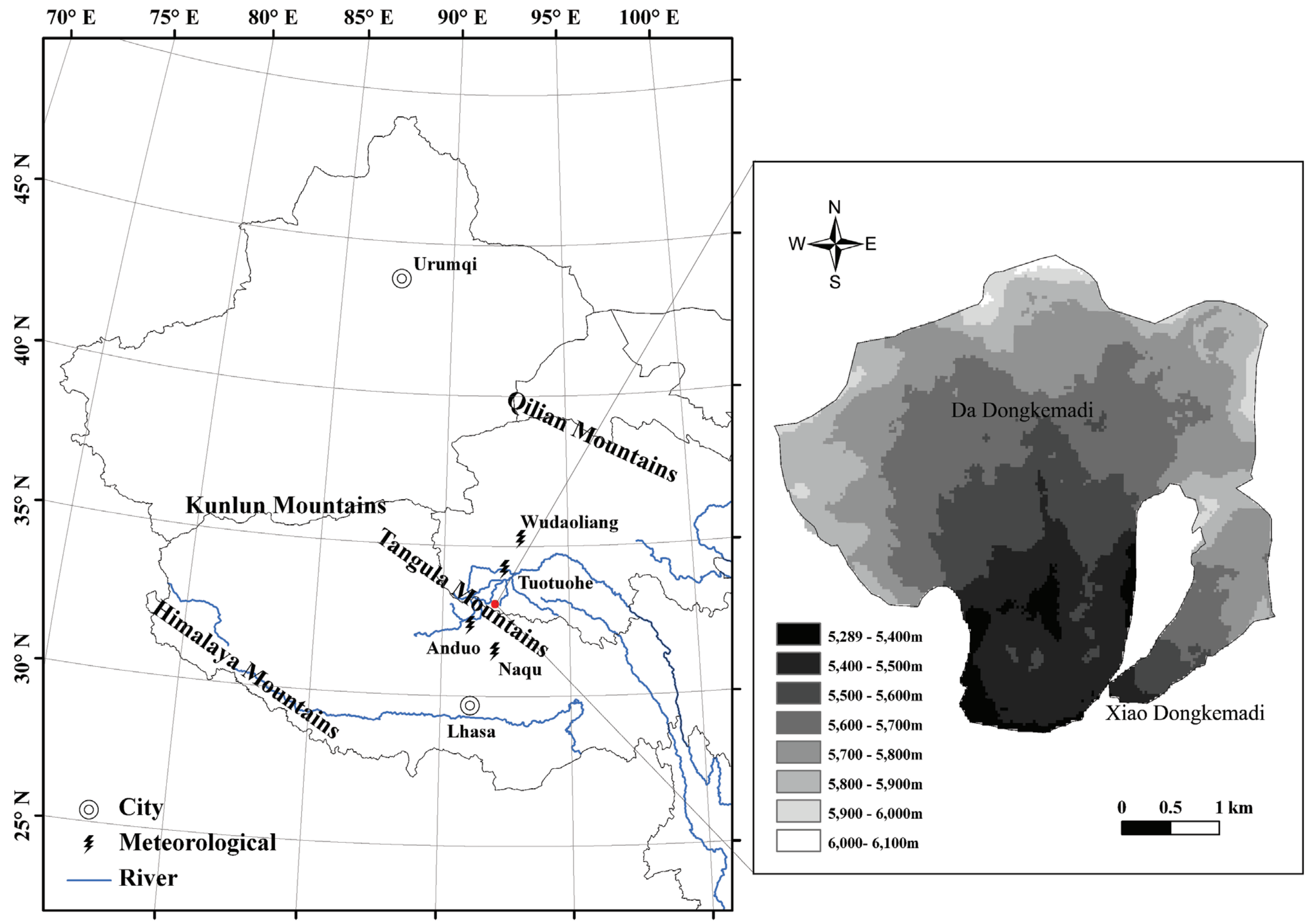

FIGURE 1. **Map of the Dongkemadi Glacier. Coordinates refer to UTM zone 46N.**

at the ablation zone while the surface on the accumulation zone was still covered by snow. Therefore, albedo pixels on the glacier were divided into two parts, the ablation zone and the accumulation zone, based on ELA location and 30 m Aster DEM. We calculated the average albedo for the ablation zone and the accumulation zone, respectively.

METEOROLOGICAL DATA

The temperature and precipitation in the Dongkemadi River basin were derived from an empirical model because of the lack of long-term meteorological data in the study glacier region. The model was built by polynomial interpolation based on AWS data from 2005 to 2008 in the Dongkemadi River basin and meteorological data of national meteorological stations near the basin. This method improved the accuracy of interpolation, and the fitted linear equation for temperature is (Gao et al., 2011):

$$T_0 = 0.473 \times T_1 + 0.116 \times T_2 + 0.035 \times T_3 + 0.424 \times T_4 - 3.149 \quad (1)$$

where T_0 represents the temperature of the Dongkemadi River basin, and T_1, T_2, T_3, and T_4 are temperatures recorded at the Anduo, Naqu, Tuotuohe, and Wudaoliang meteorological stations, respectively. The fitted equation for precipitation is:

$$P_0 = \frac{93}{93+173.8} \times \frac{472}{445.9} \times P_1 + \frac{173.8}{93+173.8} \times \frac{472}{434.9} \times P_2 \quad (2)$$

where P_0 represents the precipitation of the Dongkemadi River basin, and P_1 and P_2 are precipitation recorded at the Anduo and Naqu meteorological stations, respectively. In accordance with the above models, we reconstructed the summer and annual average temperature and precipitation of the Dongkemadi River basin from 2002 to 2012.

METHODS

The summer (from June to August) mean albedo values of the whole glacier for every year were calculated using the arithmetic mean method. Linear regression analysis was used to assess the albedo trends for each of the selected pixels on the glacier during 2002–2012:

$$T(t) = at + b \quad (3)$$

where $T(t)$ is the calculated albedo series, t is the year (t = 1, 2, …, n), and a is a trend term. A positive value of a indicates that there is an increased tendency of albedo, and a negative value of a indicates that there is a decreased trend of albedo. The magnitude of a suggests albedo changes the amount of degree. The values of a and b

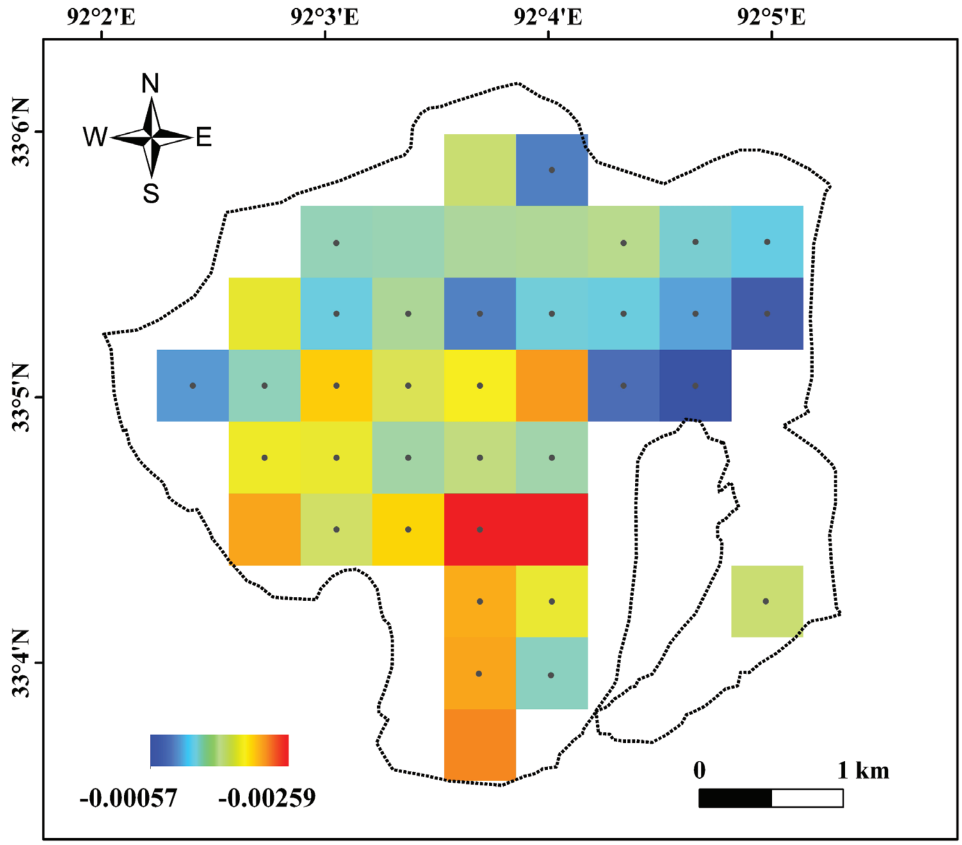

FIGURE 2. Spatial changes of inter-annual albedo for selected pixels during summer (June, July, and August) from 2002 to 2012. Stippled areas have trends that are not statistically significant above 90% confidence.

can be obtained by the least-squares method and the significance can be tested by *t*-tests.

The average values of the albedo for a 10-day moving window were calculated every fifth day for the daily albedo series. Based on this, the inter-annual variability and seasonal variations of albedos at the Dongkemadi Glacier could be obtained. Albedos in anomaly years were compared with multi-year means in summer, and change rates were calculated to quantify albedo variation.

Results

INTER-ANNUAL AND SEASONAL VARIABILITY IN ALBEDO ON DONGKEMADI GLACIER

Figure 2 shows the spatial variation tendency in the summer average albedo at the glacier. The slope of the albedo variation was gradually larger from the accumulation to the ablation zone. Decreasing tendencies that exceeded the 90% confidence level occurred for 21.9% of the glacier, which was primarily distributed on the terminus and the top of the glacier.

The inter-annual variation in average albedo on the whole Dongkemadi Glacier is shown in Figure 3. Over the ablation zone, albedo declined from 0.508 in 2002 to 0.411 in 2012 (time correlation coefficient = –0.328, p = 0.325) (Fig. 3, part a). The absolute change value (–0.097) of the albedo was more than one standard deviation (σ, ±0.089) and regression residuals (0.071). Over the accumulation zone, the albedo (time correlation coefficient = –0.353, p = 0.287) declined from 0.636 to 0.561 (absolute change value: –0.075) over the same period, and was twice as large as the regression residuals (0.034) and also exceeded one standard deviation (±0.061). The annual decline of albedo on the glacier is clearly shown in Fig. 3, part b, and the variation in average albedo in the ablation zone was more pronounced than that at the accumulation zone because of differences in meteorological conditions and in the physical properties of snow and ice.

Seasonal variations in albedo for all 11 years followed a similar pattern (Fig. 4). The mean albedo on the glacier during that time period declined from 0.73 in April to the lowest value of 0.5 by early August. Then the albedo began to increase until October. 2006, 2010, and 2012 had extremely low albedo values on the glacier. The annual lowest albedos occurred in late July, with a mean value of 0.5 from 2002 to 2012. We defined albedo anomalous years as the years in which the annual lowest albedo values were more than one standard deviation (±1σ) from the mean value. On this basis, 2006, 2010, and 2012 were anomalous years with low albedo, and the annual lowest albedo values were all less than 0.4 in July. Moreover, lower albedo values (0.54 in 2006, 0.35 in 2010, and 0.45 in 2012) appeared in June in the anomalous years.

RECONSTRUCTED TEMPERATURE AND PRECIPITATION AND LINKAGE WITH THE GLACIER ALBEDO

Table 1 shows the relationship between the mean summer albedo in the ablation and accumulation zones with precipitation and temperature. The annual and summer precipitations were significantly positively correlated with the albedo in the ablation and accumulation zones (p < 0.01). There was also a significant correlation between mean summer temperature and

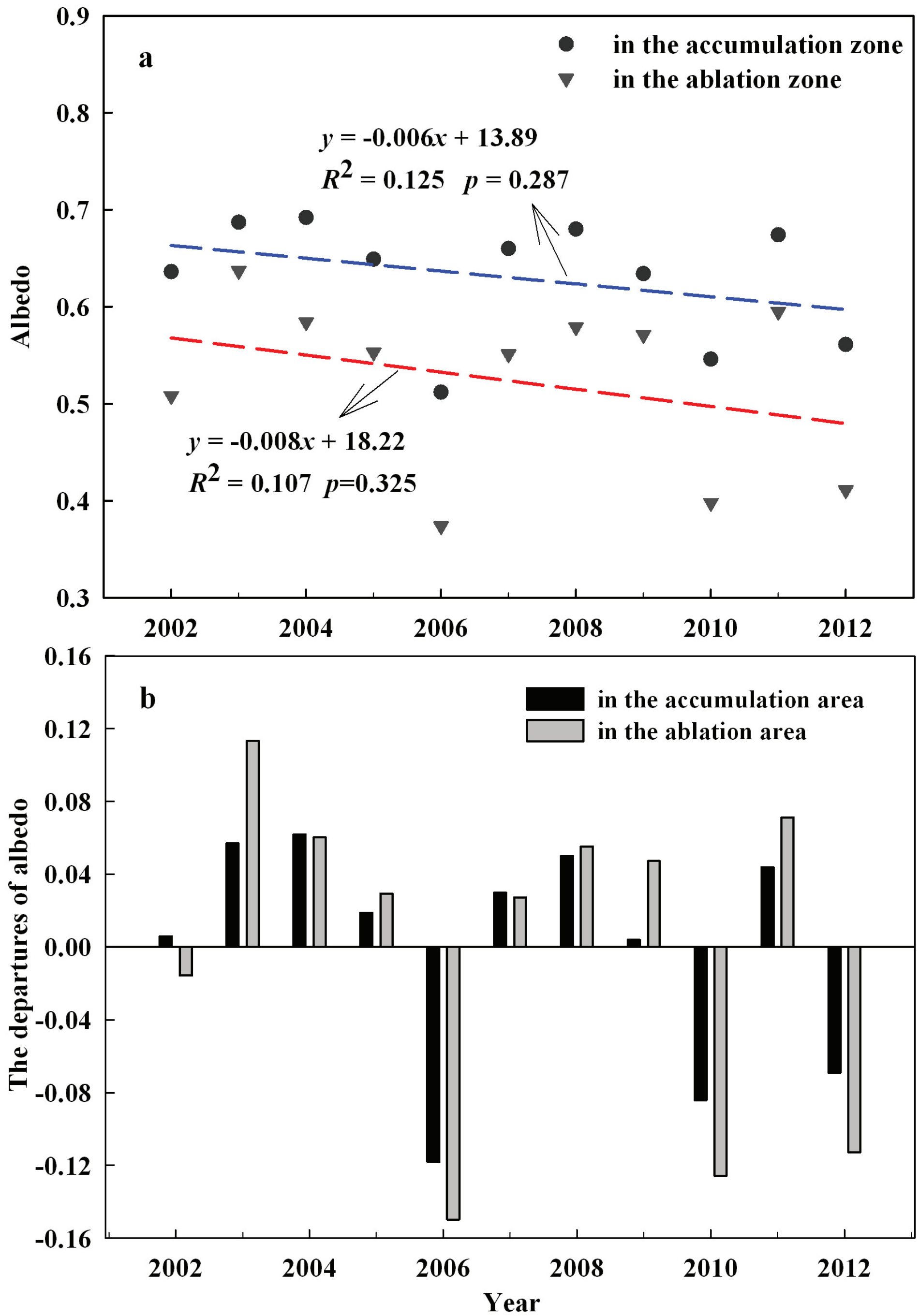

FIGURE 3. (a) Inter-annual variations of albedo on the Dongkemadi Glacier in summer. The circles indicate average albedo in the accumulation zone, and the triangles indicate average albedo in the ablation zone. The dashed line represents the trends of the albedo. (b) The departures from mean of the albedo in accumulation zone and ablation zone.

the albedo in the ablation zone ($r = -0.88$, $p < 0.005$) and the accumulation zone ($r = -0.93$, $p < 0.005$), respectively, whereas there was no significant correlation between mean annual temperature and the albedo in either the ablation zone or the accumulation zone. These relationships suggest that both the precipitation amount and the mean summer temperature affected the summer albedo on the glacier. Precipitation affected the total mass accumulation of a glacier in a year, and summer temperature affected glacier melt.

There were apparent high summer temperatures in 2006 (4.5 °C) and 2010 (4.7 °C), which were more than 1σ from the mean (Fig. 5, part a). Also, less summer precipitation occurred in 2006 (242 mm) and 2010 (263 mm) (Fig. 5, part b), which were lower than 1σ from the mean. Concurrently, lower summer albedos on the glacier also occurred in 2006 and 2010 as compared to other years (Fig. 5).

Figure 6 shows the spatial distribution of the albedo change rates on the glacier in 2003, 2006, 2008, and 2010. The albedo change rates in 2006 and 2010 were negative, ranging between –34% and –4% (Fig. 6, parts a and b). This suggests that the glacier surface albedo was anomalously low in anomalous warm and dry years. However, when the summer temperature was relatively low and the annual precipitation was relatively rich (i.e., in 2003 and 2008), the albedo on the glacier was high. The change rates of albedo on the glacier ranged from 0.8% to 32% in 2003 and from 2% to 16% in 2008 (Fig. 6, parts c and d).

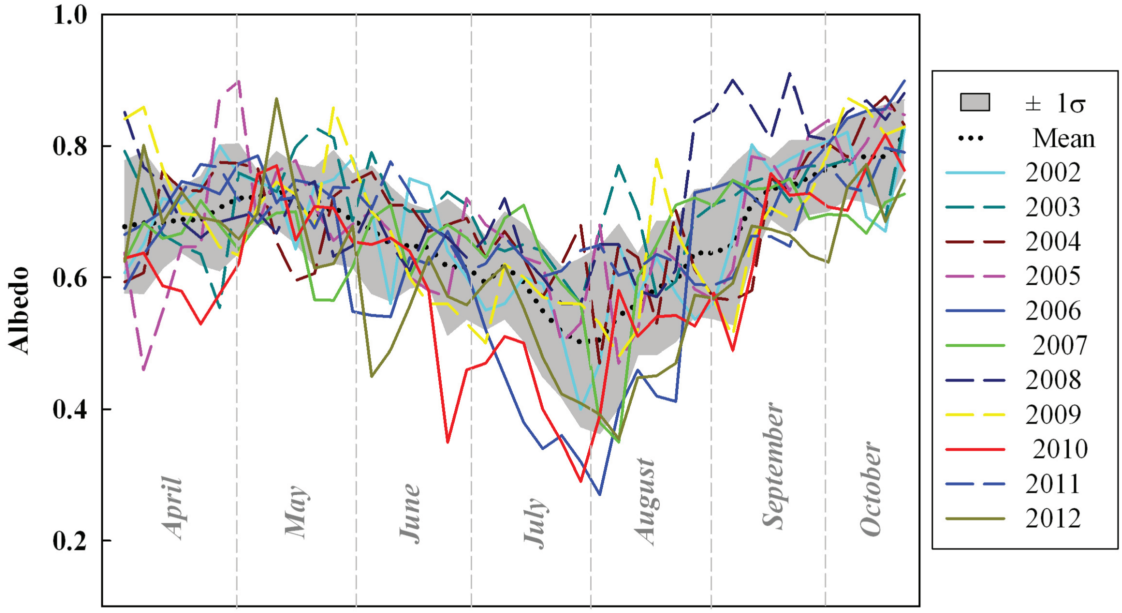

FIGURE 4. Average values of the albedo for a 10-day moving window calculated every fifth day on the Dongkemadi Glacier from MOD10A1 data. The values of one standard deviation for the 11 years are presented as the shaded area.

We also found that the area close to the equilibrium line was sensitive for albedo change. The largest albedo variation was distributed in the middle of the glacier (5500–5600 m), which is around the ELA (Fig. 6). Specifically, the albedo change rate around the ELA reached about –34% in 2006 when the summer temperature was about 1 °C higher and summer precipitation was 94.5 mm lower than the mean values of the 11 years. In 2010, the albedo change rate reached approximately –32% around the ELA, when the summer temperature was about 1.2 °C higher and summer precipitation was 73.4 mm lower than the mean values of the 11 years.

LINKING ALBEDO AND GLACIER MASS BALANCE

Mass balance is a direct and reliable indicator of glacier status. Annual variations of the mass balance observed in the Xiao Dongkemadi Glacier showed that negative mass balance appeared in the past decade. There is a decreasing tendency of mass balance on the Xiao Dongkemadi Glacier, although the trend is not statistically significant (Fig. 7, part a). The annual mass balances were close to –1000 mm w.e. in 2006 and 2010, which were much lower than the average level (–406 mm w.e.) of 2002–2010.

Associated with the albedo variations previous described, the annual lowest values of albedo on the glacier reached their minimum values of the 11-years closely corresponding to the year when major negative mass balance appeared. There was a statistically significant positive correlation between annual mass balance and the annual lowest albedos on the Xiao Dongkemadi Glacier ($r = 0.94$, $p < 0.01$). Therefore, we established a linear model using the annual lowest albedo as the dependent variable and the annual mass balance of the Xiao Dongkemadi Glacier as the independent variable (Fig.7, part b). This model can explain the relationship between the annual lowest albedo of the glacier and mass balance with a good fit ($R^2 = 0.88$, $p < 0.001$).

Based on the linear model on the Xiao Dongkemadi Glacier, we reconstructed the mass balance of the Da Dongkemadi Glacier (Table 2). The trend of mass balance of Da Dongkemadi Glacier was similar to that of Xiao Dongkemadi Glacier, but the amount of variation was not as large as that of Xiao Dongkemadi Glacier. The reason may be that the responses of glaciers with different sizes to climate change vary: the smaller of the glacier area, generally the more sensitive, is the climate response of the glacier (Zhang et al., 2011a, 2011b).

TABLE 1

Relationships between summer albedo and temperature and precipitation in the accumulation zone and the ablation zone in summer and the whole year.

Period	Albedo vs.	Accumulation zone	Ablation zone
Summer	Temperature	–0.93**	–0.87**
	Precipitation	0.89**	0.83**
Annual	Temperature	–0.64	–0.47
	Precipitation	0.76**	0.71*

*, $p < 0.01$.
**, $p < 0.005$.

Discussions

ALBEDO DECLINE ON GLACIERS AND POSSIBLE IMPACT FACTORS

The declining linear trend of albedo on the Dongkemadi Glacier from 2002 to 2012 was not statistically significant, but it

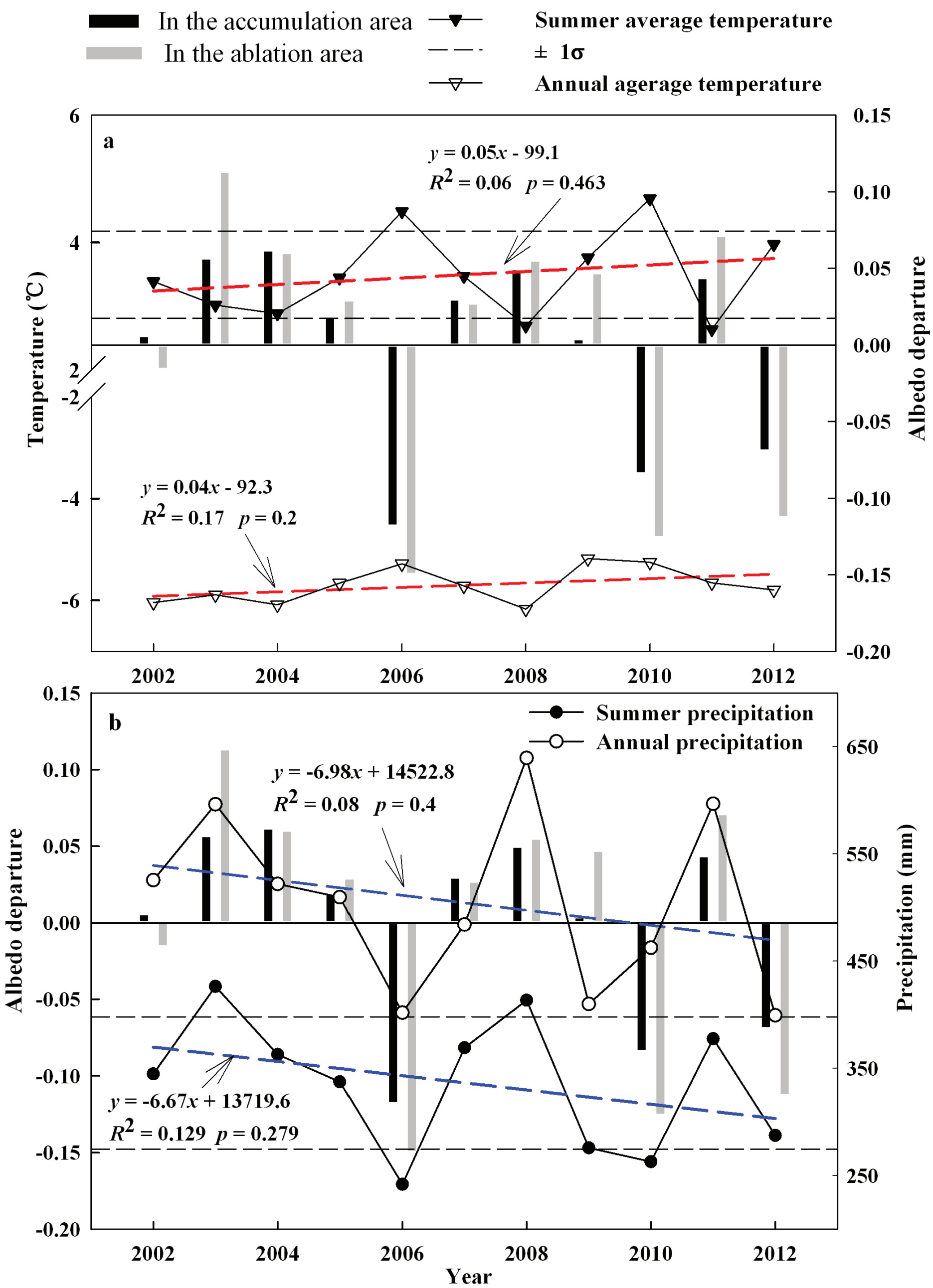

FIGURE 5. (a) Summer and annual mean temperature and (b) summer and annual precipitation derived from an empirical model associated with their trends (dashed lines). In (a) and (b), the albedo departures from the mean over the accumulation zone and the ablation zone were calculated from 2002 to 2012, which are represented by bars.

cannot be neglected. Over the ablation zone of the glacier, albedo declined from 0.508 in 2002 to 0.411 in 2012; over the accumulation zone, the albedo declined from 0.636 to 0.561 over the same period. The declining trend of albedo on other glaciers and impacts of albedo variation on glaciers have also been reported. A persistent drop in Greenland Ice Sheet surface albedo has also been observed in satellite data and climate models from 2000 to 2011, and the ablation zone albedo declined from 0.715 in 2000 to 0.632 in 2011; over the accumulation area, there was a significant linear decline from 0.817 to 0.766 over the same period (As et al., 2012). Oerlemans et al. (2009) reported that surface albedo on the Morteratsch Glacier (Swiss Alps) in summer dropped from 0.32 to 0.15 over the period 2003 to 2006, which resulted in additional removal of about 3.5 m of ice thickness in that period. Decreased albedos on glacier surfaces evidently enhance the absorption of radiation, which may also be responsible for the acceleration of glacier melting in the past 20 years (Li et al., 2007). Climate models suggest plausible estimates for the impact of albedo variation on glaciers. Albedo declines (1.5% in the Arctic and 3% in northern hemisphere land areas) yield a climate forcing of +0.3 W m^{-2} in the northern hemisphere (Hansen and Nazarenko, 2004), which enhances glacier melting.

Seasonal variation in albedo on the study glacier is clear. Albedo values in April were the highest, when cold, thick snow covered the glacier. As temperatures increased, the snow cover began to warm and melt, thereby decreasing the snow albedo. Until the end of July, when air temperature reached the annual maximum value, meltwater production peaked and ice was exposed to the greatest extent in the ablation zone, and the albedo declined to its lowest value. Then, at the end of the melt season (in late August),

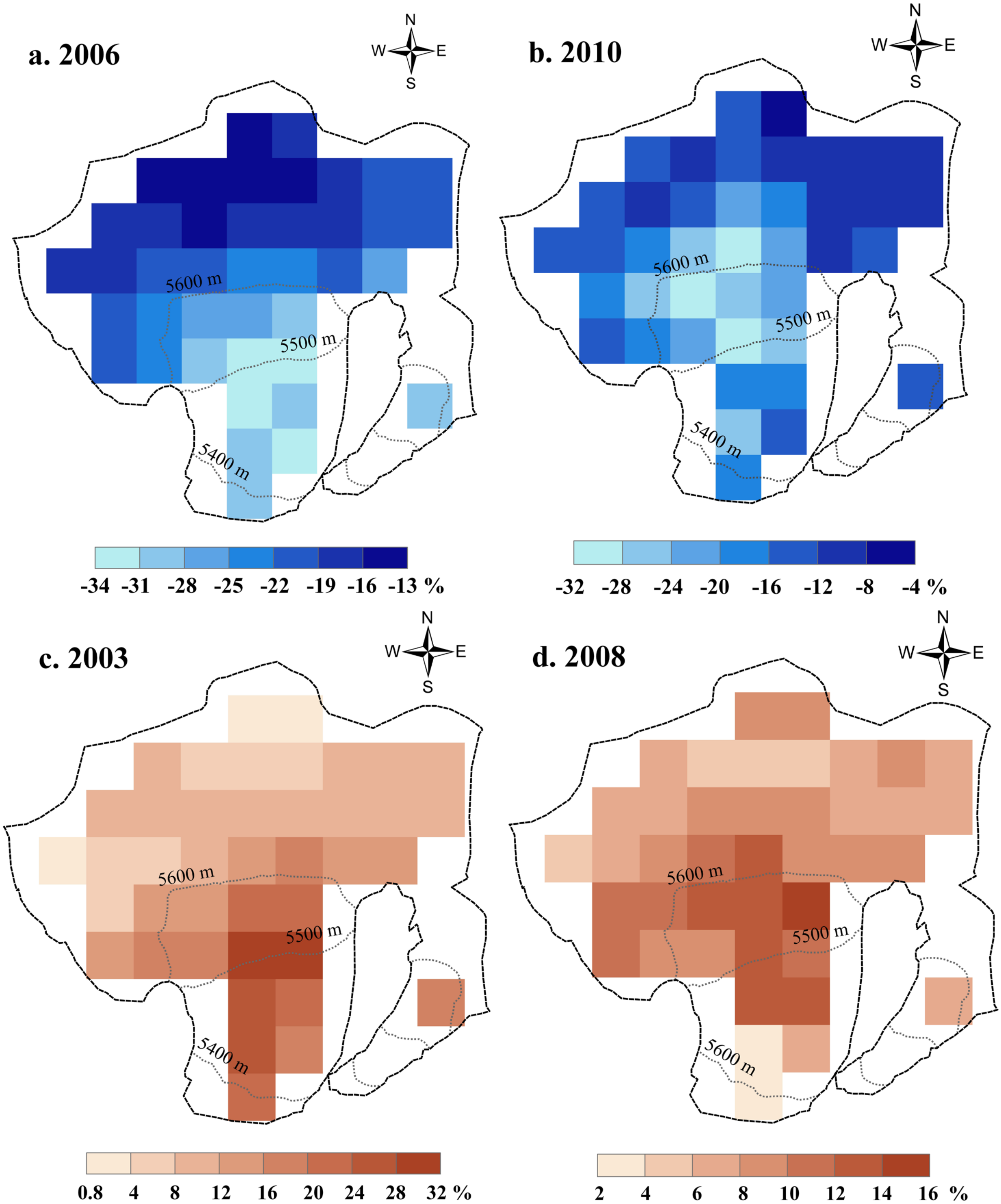

FIGURE 6. Spatial distribution of albedo change rates in the years of (a) 2006, (b) 2010, (c) 2003, and (d) 2008 on the Dongkemadi Glacier, relative to 2002–2012 means for June–August.

snow accumulation brightened the surface of the glacier, and the albedo of the glacier began to increase until October. In the Dongkemadi Glacier, extremely low albedo values were detected at the end of July (in 2006 and 2010), which means that the glacier could have experienced high melt at those years. The lower albedo values that appeared in early June in anomalous years also indicated that the snow melt was stronger than in other years during the same period.

Both precipitation and summer temperature are the dominant factors for albedo variation. The summer temperature was signifi-

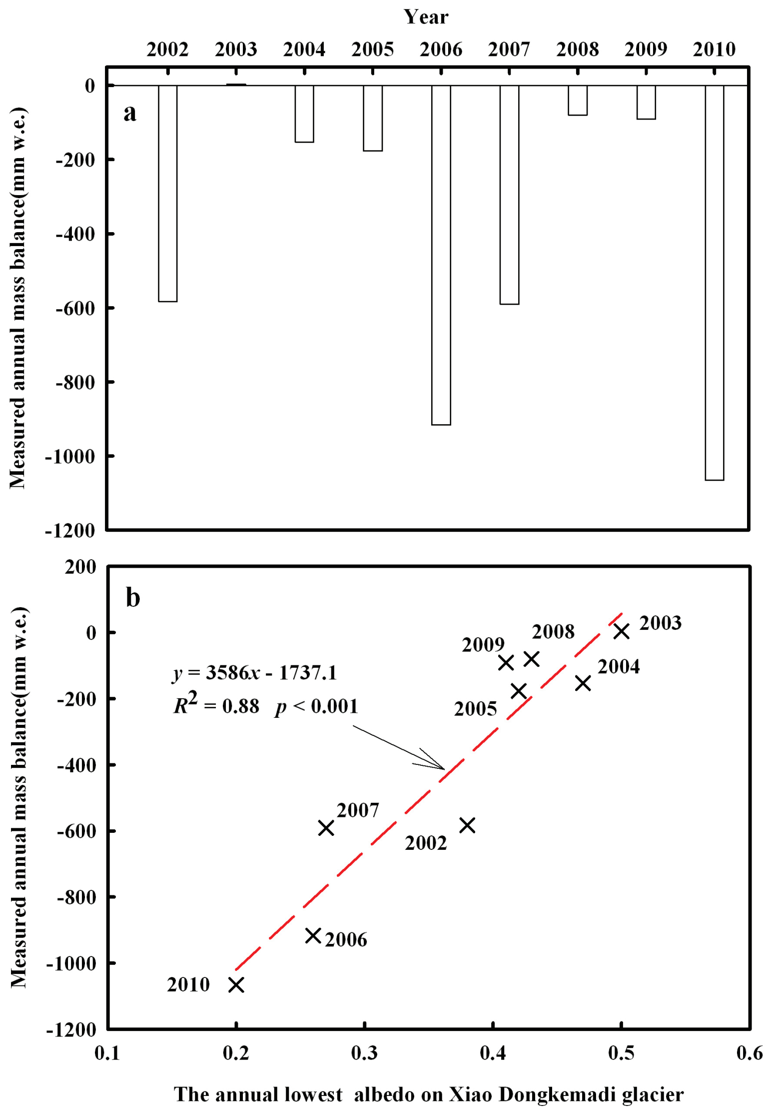

FIGURE 7. (a) Annual variations of the mass bass balance measured in the Xiao Dongkemadi Glacier from 2002 to 2010, and (b) scatter plot between measured annual mass balance and the annual lowest albedo on Xiao Dongkemadi Glacier.

TABLE 2

Estimated mass balance on the Da Dongkemadi Glacier using minimum 10-day running mean albedo.

Year	Albedo	Mass balance (mm w.e.)
2002	0.4	–302.4
2003	0.56	271.5
2004	0.47	–51.3
2005	0.47	–51.3
2006	0.27	–768.7
2007	0.35	–481.7
2008	0.56	271.5
2009	0.48	–15.4
2010	0.29	–696.9
2011	0.6	425.7
2012	0.36	–463.8

cantly negatively correlated with the summer albedo on the Dongkemadi Glacier, in both the accumulation zone and the ablation zone, during the period of 2002–2012. Air temperature physically affects the reflectance properties of the surface material on the glacier, such as snow metamorphism and increases in the concentration of light-absorbing impurities in snow or on ice (Brock et al., 2000a). Temperature rise in the summer leads to snow grain metamorphosis change in the accumulation zone. The thickness of the firn layer becomes thin, the amount of fine firn with high reflectivity is reduced, and the amount of coarse firn with low reflectivity is increased. Thus, high temperature would cause a decline in albedo in the accumulation zone as a whole. In the ablation zone, higher summer temperature would accelerate ice melting and increase the water content of the glacier surface, lowering the surface albedo.

Precipitation primarily affects the annual mass accumulation of glaciers. Decreasing precipitation reduces the glacial accumulation in the summer and exposes ice over time, which accelerates the melting process of glaciers. At the same time, meltwater on the surface of glaciers contains many dust particles during transport, and microorganisms attached to the surface of glaciers proliferate with the rise of temperature. These

FIGURE 8. Dongkemadi Glacier in May 2004 and in May 2010. The upper photos were taken at the front of the glacier tongue; the lower photos were taken at the lateral moraine of the glacier.

deepen the ice color, thereby significantly reducing the surface reflectivity. This phenomenon is more likely to happen over the ablation zone. Figure 8 compares two groups of photos taken on the Dongkemadi Glacier in May 2004 and May 2010. The surface of the glacier was dirtier in May 2010 compared to May 2004. From research in this study, summer average albedos and lowest albedos all were very low in 2010 compared to 2004; and the mass balances also presented a major negative balance. So, lower albedo in 2010 was more likely to be affected by dust on the surface of the glacier. A similar result was also found in a previous study. Fujita et al. (2000) observed a drastic melt on the Dongkemadi Glacier from May to June in 1995, which they considered to have been caused by low surface albedo due to dust deposition, even under low-air-temperature conditions. Since 2000, declining trends in the albedo of Himalayan glaciers have been detected; their upper areas have become darker, and light-absorbing constituents (e.g., black carbon and dust) could be partly responsible for this phenomenon (Ming et al., 2012).

MECHANISM OF ALBEDO CHANGE AROUND THE ELA

The ELA is an important parameter in describing a glacier because it helps to define the relation between the local climate and the distribution of glacier mass (Fountain et al., 1999). Compared to other areas on the study glacier, the change rates in albedo around the ELA were larger. The area near the ELA on the glacier is sensitive and may fall or rise due to temperature changes during the ablation season. A glacier advances when the ELA falls and retreats when the ELA rises (Wang et al., 2010). In a positive mass balance year when the glacier ELA falls, the original bare ice surface is replaced by snow or firn and the surface albedo rises steeply (Yao, 1987), and the energy of the glacier thus decreases. Conversely, in a negative mass balance year when the glacier ELA rises, the snow or firn area is uplifted again and the surface albedo decreases to the original area. This mechanism can explain why the albedo change in the area near the ELA is larger than in other areas on the glacier.

POTENTIAL TO ESTIMATE ANNUAL MASS BALANCE OF THE GLACIER BY THE ANNUAL LOWEST ALBEDO

The change in glacier mass balance on the Tibetan Plateau can serve as a signal of local climatic change. Herein a strong correlation between the measured annual mass balance and the annual lowest albedo of the glacier was established based on the physical mechanism. Glacier surface melt is highly sensitive to albedo variations, since surface energy balances during the ablation season are commonly dominated by receipt of solar radiation (Brock et al., 2000b). Similar results also reported that the modeled surface mass balance is highly sensitive to surface albedo (van Angelen et al., 2012). Positive melt-albedo feedback results in lower albedo on the glacier in high-melt years. For the Dongkemadi Glacier, the years of 2006, 2010, and 2012 were high-melt years, which can be proved by the field measurement of ELA. The higher observed ELA (5840 m; unpublished data) occurred on the Xiao Dongkemadi Glacier in the lower mass balance year 2005/2006, which was about 200 m higher than the average value of 5650 m (1989–2002) (Pu et al., 2008). Similar results were reported on the other glaciers on the Tibetan Plateau, and a higher observed ELA also occurred on the Qiyi Glacier located in the Qilian Mountains in the north of the Tibetan Plateau in 2005/2006, reaching the highest level (5131 m) close to the glacier summit in recent years (Wang et al., 2010). The observed ELA on the Xiao Dongkemadi Glacier in 2009/2010 reached 5780 m (unpublished data), which was about 130 m higher than the average value. It can be concluded that the year when the annual lowest albedo reached to minimum was consistent with the year when the major negative mass balance appeared and the ELA reached the highest position during the period of 2002–2012.

Even though annual mass balance on the Da Dongkemadi Glacier was estimated using the linear model based on annual lowest albedo of the glacier, this method needs to be tested on several glaciers in China. Empirical models for different glaciers in the world may vary, and the study methods to connect albedo and mass balance are slightly different; this is a valid subject for future glacier researches.

Conclusions

Monitoring the spatiotemporal variation in albedo on glaciers is a significant task, and it is valuable for simulating glacier mass balance and reflecting regional climate change. Our 11-year series of albedo values derived from satellite images and 8 years of annual measured mass balance on the Xiao Dongkemadi Glacier were analyzed for the albedo tendency of the glacier surface on multi-annual timescales and to link the two variables. The summer mean albedo over the Dongkemadi Glacier declined from 2002 to 2012, and albedo variation in the ablation zone during the period was more pronounced than that in the accumulation area because of differences in meteorological conditions and the physical properties of snow and ice. Precipitation, summer temperature, and dust on the glacier surface all play critical roles in summer mean albedo variation on the Dongkemadi Glacier. In this study, several anomalous years were found on the Dongkemadi Glacier, which were high-melt years with lower albedo and major negative mass balance. In addition, we found that the region around the ELA on the glacier was very sensitive to albedo change. There was a strong positive correlation between annual mass balance and the annual lowest albedo on the Xiao Dongkemadi Glacier during the ablation season. Consequently, it can be considered that the annual lowest albedo of a glacier could be a reasonable proxy for the annual mass balance of a glacier. If global warming continues in the future, glacier albedos in summer would become lower and mass balance would become more negative, resulting in continuous glacier retreat.

Admittedly, much uncertainty is introduced in the study process. For instance, the MODIS albedo algorithm does not provide a surface albedo estimate under cloudy skies. Our inspection of the raw MOD10A1 images revealed an abundance of residual cloud artifacts (shadows, contrails, and thin clouds) in the albedo product. The combination of other remote sensing data and a proper suggested model is necessary for further cryospheric research.

Acknowledgments

The authors thank NASA for providing image data, and the China Meteorological Data Sharing Service System for providing meteorological data. This work was supported by the National Natural Science Foundation of China (grant no. 41190084), Strategic Priority Research Program (B) of Chinese Academy of Sciences (grant no. XDB03030200), and the Young Talents funding of the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences (grant no. Y35111001). We also thank the anonymous reviewers and editors, whose comments and suggestions helped us to improve the quality of this paper.

References Cited

As, D. V., Hubbard, A., Hasholt, B., Mikkelsen, A., Broeke, M., and Fausto, R., 2012: Large surface meltwater discharge from the Kangerlussuaq sector of the Greenland ice sheet during the record-warm year 2010 explained by detailed energy balance observations. *The Cryosphere*, 6: 199–209.

Brock, B. W., Willis, I. C., and Sharp, M. J., 2000a: Measurement and parameterization of albedo variations at Haut Glacier d'Arolla, Switzerland. *Journal of Glaciology*, 46(155): 675–688.

Brock, B. W., Willis, I. C., Sharp, M. J., and Arnold, N. S., 2000b: Modelling seasonal and spatial variations in the surface energy balance of Haut Glacier d'Arolla, Switzerland. *Annals of Glaciology*, 31: 53–62.

Dumont, M., Gardelle, J., Sirguey, P., Guillot, A., Six, D., Rabatel, A., and Arnaud, Y., 2012: Linking glacier annual mass balance and glacier albedo retrieved from MODIS data. *The Cryosphere Discussion*, 6: 2363–2398.

Fassnacht, S., Brogan, D., Sexstone, G., Jasinski, M., Lopez-Moreno, J. I., and Skordahl, M., 2012: Spatio-temporal variability of snowpack properties: Comparing operational, field, and ICESat remote sensing data over Northern Colorado, United States. *In* Proceedings, Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International. Piscataway, New Jersey: IEEE, 1576–1577.

Flanner, M., Shell, K., Barlage, M., Perovich, D., and Tschudi, M., 2011: Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008. *Nature Geoscience*, 4: 151–155.

Fountain, A. G., Lewis, K. J., and Doran, P. T., 1999: Spatial climatic variation and its control on glacier equilibrium line altitude in Taylor Valley, Antarctica. *Global and Planetary Change*, 22: 1–10.

Fujita, K., Ageta, Y., Jianchen, P., and Tandong, Y., 2000: Mass balance of Xiao Dongkemadi Glacier on the central Tibetan Plateau from 1989 to 1995. *Annals of Glaciology*, 31: 159–163.

Gao, H., He, X., Ye, B., and Gao, X., 2011: The simulation of HBV hydrology model in the Dongkemadi River basin, headwater of the Yangtze River. *Journal of Glaciology and Geocryology*, 33(1): 171–181 (in Chinese with English abstract).

Greuell, J., Kohler, J., Obleitner, F., Glowacki, P., Melvold, K., Bernsen, E., and Oerlemans, J., 2007: Assessment of interannual variations in the surface mass balance of 18 Svalbard glaciers from the Moderate Resolution Imaging Spectroradiometer/Terra albedo product. *Journal of Geophysical Research*, 112(2007): D07105/07101–D07105/07111, http://dx.doi.org/10.1029/2006JD007245.

Hansen, J., and Nazarenko, L., 2004: Soot climate forcing via snow and ice albedos. *Proceedings of the National Academy of Sciences of the United States of America*, 101(2): 423–428.

Immerzeel, W., Droogers, P., De Jong, S., and Bierkens, M., 2009: Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. *Remote Sensing of Environment*, 113: 40–49.

Jiang, X., Wang, N., He, J., Wu, X., and Song, G., 2010: A distributed surface energy and mass balance model and its application to a mountain glacier in China. *Chinese Science Bulletin*, 55(33): 2079–2087.

Kwok, R., and Rothrock, D., 2009: Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008. *Geophysical Research Letters*, 36: L15501, http://dx.doi.org/10.1029/2009GL039035.

Kylling, A., Dahlback, A., and Mayer, B., 2000: The effect of clouds and surface albedo on UV irradiances at a high latitude site. *Geophysical Research Letters*, 27: 1411–1414.

Li, Z., Shen, Y., Wang, F., Li, H., Dong, Z., Wang, W., and Wang, L., 2007: Response of glacier melting to climate change. *Journal of Glaciology and Geocryology*, 29(3): 333–342 (in Chinese with English abstract).

Liang, X. Z., Xu, M., Gao, W., Kunkel, K., Slusser, J., Dai, Y., Min, Q., Houser, P. R., Rodell, M., and Schaaf, C. B., 2005: Development of land surface albedo parameterization based on Moderate Resolution Imaging Spectroradiometer (MODIS) data. *Journal of Geophysical Research*, 110(D11): 16, http://dx.doi.org/10.1029/2004JD005579.

Ming, J., Du, Z., Xiao, C., Xu, X., and Zhang, D., 2012: Darkening of the mid-Himalaya glaciers since 2000 and the potential causes. *Environmental Research Letters*, 7(1): 014021, http://dx.doi.org/10.1088/1748-9326/7/1/014021.

Munneke, P. K., Van den Broeke, M., Lenaerts, J., Flanner, M., Gardner, A., and Van de Berg, W., 2011: A new albedo parameterization for use in climate models over the Antarctic ice sheet. *Journal of Geophysical Research*, 116: D05114, http://dx.doi.org/10.1029/2010JD015113.

Oerlemans, J., and Knap, W., 1998: A year record of global radiation and albedo in the ablation zone of Morteratschgletscher, Switzerland. *Journal of Glaciology*, 44: 231–238.

Oerlemans, J., Giesen, R., and Van Den Broeke, M., 2009: Retreating alpine glaciers: increased melt rates due to accumulation of dust (Vadret da Morteratsch, Switzerland). *Journal of Glaciology*, 55(192): 729–736.

Pedersen, C. A., and Winther, J. G., 2005: Intercomparison and validation of snow albedo parameterization schemes in climate models. *Climate Dynamics*, 25(4): 351–362.

Perovich, D. K., and Polashenski, C., 2012: Albedo evolution of seasonal Arctic sea ice. *Geophysical Research Letters*, 39: L08501, http://dx.doi.org/10.1029/2012GL051432.

Pu, J., and Yao, T., 1993: *Study on Mass Balance of Small Dongkemadi Glacier*. Beijing: Science Press (in Chinese with English abstract).

Pu, J., Yao, T., Zao, Y., Seko, K., and Fujita, K., 1995: Mass balance on the Dongkemadi and Meikuang Glaciers in 1992/1993. *Journal of Glaciology and Geocryology*, 17(2):138–143 (in Chinese with English abstract).

Pu, J., Yao, T., Yang, M., Tian, L., Wang, N., Ageta, Y., and Fujita, K., 2008: Rapid decrease of mass balance observed in the Xiao (Lesser) Dongkemadi Glacier, in the central Tibetan Plateau. *Hydrological Processes*, 22: 2953–2958.

Ramillien, G., Lombard, A., Cazenave, A., Ivins, E., Llubes, M., Remy, F., and Biancale, R., 2006: Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE. *Global and Planetary Change*, 53: 198–208.

Schaepman-Strub, G., Schaepman, M., Painter, T., Dangel, S., and Martonchik, J., 2006: Reflectance quantities in optical remote sensing: definitions and case studies. *Remote Sensing of Environment*, 103: 27–42.

Shea, J., Menounos, B., Moore, R. D., and Tennant, C., 2012: Regional estimates of glacier mass change from MODIS-derived equilibrium line altitudes. *The Cryosphere Discussions*, 6: 3757–3780.

Stroeve, J. C., Box, J. E., Fowler, C., Haran, T., and Key, J., 2001: Intercomparison between in situ and AVHRR Polar Pathfinder–derived surface albedo over Greenland. *Remote Sensing of Environment*, 75: 360–374.

Stroeve, J. C., Box, J. E., and Haran, T., 2006: Evaluation of the MODIS (MOD10A1) daily snow albedo product over the Greenland ice sheet. *Remote Sensing of Environment*, 105: 155–171.

Sun, W., Qin, X., Ren, J., Yang, X., Zhang, T., Liu, Y., Cui, X., and Du, W., 2012: The surface energy budget in the accumulation zone of the Laohugou Glacier No. 12 in the western Qilian Mountains, China, in summer 2009. *Arctic, Antarctic, and Alpine Research*, 44(3): 296–305.

Tedesco, M., Fettweis, X., Van den Broeke, M., Van de Wal, R., Smeets, C., van de Berg, W. J., Serreze, M., and Box, J., 2011: The role of albedo and accumulation in the 2010 melting record in Greenland. *Environmental Research Letters*, 6: 014005, http://dx.doi.org/10.1088/1748-9326/6/1/014005.

Tekeli, A. E., Şensoy, A., Şorman, A., Akyürek, Z., and Şorman, Ü., 2006: Accuracy assessment of MODIS daily snow albedo retrievals with in situ measurements in Karasu basin, Turkey. *Hydrological Processes*, 20(4): 705–721.

van Angelen, J. H., Lenaerts, J. T. M., Lhermitte, S., Fettweis, X., Kuipers Munneke, P., van den Broeke, M. R., van Meijgaard, E., and Smeets, C. J. P. P., 2012: Sensitivity of Greenland Ice Sheet surface mass balance to surface albedo parameterization: a study with a regional climate model. *The Cryosphere*, 6: 1175–1186.

Wang, N., He, J., Pu, J., Jiang, X., and Jing, Z., 2010: Variations in equilibrium line altitude of the Qiyi Glacier, Qilian Mountains, over the past 50 years. *Chinese Science Bulletin*, 55(33): 3810–3817.

Wang, J., Ye, B., Cui, Y., Yang, G., He, X., and Sun, W., 2011: Accuracy assessment of MODIS daily snow albedo product based on scaling transformation. *In* Proceedings, Remote Sensing, Environment and Transportation Engineering (RSETE), 2011 International Conference. Piscataway, New Jersey: IEEE, 2865-2870.

Yang, X., Qin, D., Zhang, T., Kang, S., Qin, X., and Liu, H., 2010: Seasonal characteristics of surface radiative fluxes on the East Rongbuk Glacier in the north slope of Mt. Qomolangma (Mt. Everest) region. *Acta Meteorologica Sinica*, 68(1): 19–31(in Chinese with English abstract).

Yao, T., 1987: The relationship between glacial mass balance equilibrium line and climate. *Journal of Glaciology and Geocryology*, 9(4): 289–300 (in Chinese with English abstract).

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., and Xu, B., 2012: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change*, 2: 663–667.

Zhang, H., Lu, A., Wang, L., Guo, Z., and Zhang, C., 2011a: Glacier change in the Shulenan Mountain monitored by remote sensing. *Journal of Glaciology and Geocryology*, 33(1): 8–13 (in Chinese with English abstract).

Zhang, M., Wang, S., Li, Z., and Wang, F., 2011b: Variation of glacier area in China against the warming in the past 50 years. *Acta Geographica Sinica*, 66(9): 1155–1165 (in Chinese with English abstract).

MS accepted June 2014