Darkening of the mid-Himalaya glaciers since 2000 and the potential causes

Jing Ming\textsuperscript{1,2,5}, Zhencai Du\textsuperscript{3}, Cunde Xiao\textsuperscript{1,4}, Xiaobin Xu\textsuperscript{4} and Dongqi Zhang\textsuperscript{1,4}

\textsuperscript{1} State Key Laboratory of Cryospheric Sciences (SKLCS), CAREERI, CAS, Lanzhou 730000, People’s Republic of China
\textsuperscript{2} China National Climate Center (CNCC), Beijing 100081, People’s Republic of China
\textsuperscript{3} Institute of Atmospheric Physics, CAS, Beijing 100029, People’s Republic of China
\textsuperscript{4} Chinese Academy of Meteorological Sciences, Beijing 100081, People’s Republic of China

E-mail: petermingjing@hotmail.com

Received 29 October 2011
Accepted for publication 26 January 2012
Published 22 February 2012
Online at stacks.iop.org/ERL/7/014021

Abstract
Himalayan glaciers are a vital water source for people in the high regions of Asia. Their complete melting would be a crisis for approximately 1 billion people. Albedo is one of the key parameters that affect the energy balance of the snow and ice surfaces. Since 2000, albedos have been retrieved from satellite data for eleven representative Himalayan glaciers. It was found that most of the glaciers showed declining trends in the albedo of their upper areas, indicating that they have generally become darker in the past decade. A simulation case study in conjunction with \textit{in situ} measurements showed that light-absorbing constituents (e.g., black carbon and dust) could be partly responsible for this phenomenon during late springtime; the background regional warming could also be responsible. The current surface radiation absorption in Himalayan glaciers could lead to significant melting, causing most of them to be in danger of rapid mass loss.

Keywords: Himalayan glaciers, black carbon, dust, melt, albedo

1. Introduction
Himalayan glaciers are an irreplaceable water resource for the Asian inter-boundary rivers. Their accelerated melting and the sustainable usage of water are currently among the most important issues for society (Parry \textit{et al} 2007, Kang \textit{et al} 2010). More than one billion people rely on the fresh water that originates from these glaciers (Immerzeel \textit{et al} 2010). Their rapid melting is related to both the darkening effect associated with atmospheric brown clouds (ABCs) that contain light-absorbing constituents (LACs), including black carbon (BC) and dust, and the regional warming caused by greenhouse gases (Ramanathan \textit{et al} 2007, Ramanathan and Carmichael 2008). Increasing BC emissions from South Asia since accelerated industrialization (1950–2000) (Bond \textit{et al} 2007) could cause more BC to be deposited on these glaciers.

As modeling results show (Flanner \textit{et al} 2009), Himalayan glaciers are highly affected by the snow/ice (S/I) darkening effect. The S/I darkening effect refers to the reduction of albedo caused by LACs that are deposited on the S/I surface (Painter \textit{et al} 2007, Warren and Wiscombe 1980) and by natural aging (Warren and Wiscombe 1980). The S/I albedo, defined as the ratio of the reflected radiation to the incident radiation on the S/I surface, is a key parameter that affects the energy balance of the S/I cover (Armstrong and Brun 2008). S/I albedo lowering indicates that less radiation is reflected into space and more is absorbed by the S/I, causing the surface to become darker and facilitating melting. Earlier studies have addressed the impact of LACs on Himalayan glaciers and snow melting (Ming \textit{et al} 2008, Menon \textit{et al} 2010, Yasunari \textit{et al} 2010), but these were mostly based on...
modeling (Menon et al 2010, Qian et al 2011) or single-point measurements (Ming et al 2008, Yasunari et al 2010). In this study, we try to determine the variation in the albedo over a period of ten years for multiple glaciers at different locations in the Himalayas, and we discuss the potential causes based on satellite observations and in situ measurements.

2. Methods

2.1. Study area description and selection of sites

It is generally believed that westerly winds and the monsoons alternately dominate the synoptic system in the Himalayas during the winter and summer (Thompson et al 2000). The prevailing winds, aerosol optical depth (AOD) and topography surrounding the study area are depicted in figure 1. The regions surrounding the high Himalayas, such as the Thar Desert and the Indo-Gangetic Basin, emit large quantities of LACs (dust and BC) (Prasad et al 2009). Recent studies have suggested that aerosols (industrial sulfate, trace metals and BC) in polluted air from South Asia could be lifted up over the Himalayas and carried to the Tibetan Plateau (Ming et al 2007, Loewen et al 2007, Ming et al 2009).

We selected eleven glacial sites in the mid-Himalaya region, of which five were situated on the northern slopes of the range and six were on the southern slopes with six pairs of back-to-back orientations. These glacial sites were geographically situated at longitudes in the range of 80°–90°E, where the atmospheric environment is strongly affected by a suspended thick aerosol layer. The five sites on the northern slopes have been investigated for decades by Chinese researchers, and their geographic positions were precisely measured by high-resolution ground GPS devices; the locations of the six sites on the southern slopes were determined from satellite images from the World Wind software released by NASA (reference website in table 1).

2.2. Albedo data retrieval

For the period from 2000 to 2009, we selected the daily snow product (MOD10A1 V005) from the data recorded by the Moderate-Resolution Imaging Spectroradiometer (MODIS) on board the Terra satellite, which can be obtained from...
the MODIS cloud mask and as 100% snow-covered by the MOD10A1 should work well. The albedo values were of a 1200 km snow cover and quality assessment (QA) data, which consist This product contains the snow cover, snow albedo, fractional the MODIS website (http://nsidc.org/data/mod10a1v5.html).

Like polar ice sheets or snow cover, most Himalayan glaciers are typically shallow and long and are much smaller
23-04-2007 FS-2 9.22 65.33
04-05-2007 FS-4 8.64 65.67
05-05-2007 FS-5 15.79 104.00
06-05-2007 FS-6 7.08 33.54
08-05-2007 FS-7 1.09 14.66
09-05-2007 FS-8 1.43 6.49
10-05-2007 FS-9 0.45 9.38
11-05-2007 FS-10 8.29 38.14
Average — 8.76 54.11

Table 1. Description of the selected glacial sites.

| ID     | Glacier name         | Latitude (°N) | Longitude (°E) | Altitude (m) | Remark                      | Location  | Source                  |
|--------|----------------------|---------------|----------------|--------------|-----------------------------|-----------|-------------------------|
| NM     | Naimona’nyi          | 30.45         | 81.27          | 5850         | Measured in field           | China     | Xu et al (2006)         |
| GM     | Gymayangzong         | 30.21         | 82.16          | 5561         | Measured in field           | China     | This work               |
| KW     | Kangwure             | 28.47         | 85.82          | 6000         | Measured in field           | China     | Xu et al (2006)         |
| ER     | East Rongbuk         | 28.02         | 86.96          | 6517         | Measured in field           | China     | This work               |
| QY     | Qiangyong            | 28.86         | 90.22          | 5400         | Measured in field           | China     | Xu et al (2006)         |
| PT1    | N/A                  | 29.80         | 81.10          | 4876         | Read from World Windb       | Southern Asia | This work   |
| PT2    | N/A                  | 29.91         | 82.22          | 4951         | Read from World Windb       | Southern Asia | This work   |
| PT3    | N/A                  | 28.16         | 85.80          | 5351         | Read from World Windb       | Southern Asia | This work   |
| PT4    | N/A                  | 27.83         | 87.02          | 5784         | Read from World Windb       | Southern Asia | This work   |
| PT5    | N/A                  | 27.90         | 90.30          | 5222         | Read from World Windb       | Southern Asia | This work   |
| PT6    | N/A                  | 27.81         | 91.38          | 4369         | Read from World Windb       | Southern Asia | This work   |

The altitude refers to the location where the pixel data were retrieved for the albedo value.

The World Wind software is developed by NASA and can be downloaded for free: http://worldwind.arc.nasa.gov/java/.

2.3. Snow sampling from the East Rongbuk (ER) glacier and LAC content measurement

During a field campaign in 2007, ten fresh snow samples were collected from the saddle of the ER glacier (table 2, figure 2). The procedures for the sampling, transportation and storage of the snow followed those used in a previous study (Ming et al 2009). The pretreatment of the snow samples was performed at the State Key Laboratory of Cryospheric Sciences (Chinese Academy of Sciences, Lanzhou). In a 100-class clean room, the snow samples were completely melted at room temperature within 1 h. The melted samples were filtered with the help of a hand vacuum pump and quartz filters which had been preheated for 24 h at 600 °C to eliminate possible carbon content. Hydrochloric acid (2%–4%) was added to the filters to remove any possible carbonates, and then the filters were allowed to dry.

The dust content in the snow samples was calculated by subtracting the weight of the blank filter from the weight of the filter with the sample, as weighed by a laboratory balance (Mettler Toledo TMX5 with an accuracy of 1 µg). To measure the mass of BC, the sample filters were then analyzed using a Ströhlein Coulomat 702C® with a detection limit of 3 µgC and a precision of 0.02 µgC. For high temperatures of over 1000 °C and with a pure oxygen stream, the BC content in the filters was completely oxidized to CO2. The acidification of the solution by CO2 activated back-electrolysis to recover the initial pH value. The quantity of electricity required for this process could be used to calculate the amount of CO2, which could then be converted to the equivalent BC mass. A more detailed description of this analysis can be found in a previous study (Cachier and Pertuisot 1994).

3. Results and discussion

3.1. Trends in the albedos of Himalayan glaciers since 2000

The seasonal albedo variations were different on the southern and northern slopes of the Himalayas. Generally, the glaciers on the northern slopes exhibited higher albedos in the summer,
3.2. Real versus ideal: the albedos of snow from satellite data and of simulated pristine snow on Himalayan glaciers

The albedo of a typical fresh snowpack is usually 0.80–0.95 in the visible spectrum, but after a few days it can drop to ~0.5 or even lower due to aging, melting and accumulation of impurities (Wiscombe and Warren 1980). To simulate the albedos of pristine snow on the glacier surfaces, we used a snow–ice–aerosol radiative (SNICAR) model (Flanner et al. 2007), assuming an effective snow grain radius of 150 µm and a density of 150 kg m$^{-3}$ with no LACs. The ten year running averages of the daily and monthly albedos were calculated at the sites to show the seasonal variations (figure 5). On average, the albedo of the simulated pristine snow was 19 ± 10% (7%–35%) higher than the satellite observations during 2000–9. The mean declines in the albedos were 24% on the northern slopes and 15% on the southern slopes, which could also be interpreted as being primarily caused by more frequent precipitation on the southern slopes.

3.3. The radiation absorption of Himalayan glaciers in the post-deposition process

From fresh snow that has fallen to the aged post-deposition snow, the enhanced solar absorption by Himalayan glaciers could be considered to be a type of forcing that accelerates melting. The surface radiation data based on elevation were retrieved from the NASA data based on satellite observations, ground observations, and modeling with a spatial-resolution grid of 1° × 1° (http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi?+s01#s01) at the locations of the glaciers (figure 6). The intra-annual variation in the solar radiation between the sites was similar due to their geographic proximity to one another and varied from approximately 200 W m$^{-2}$ in winter to 400 W m$^{-2}$ in summer. The intra-annual forcing at each site was calculated by multiplying the downwelling radiation in
the site’s grid by the difference between the simulated pristine albedo and the satellite observation albedo (figure 7). The annual mean forcing was $57 \pm 24$ W m$^{-2}$, most of which could be attributed to BC, dust and natural aging.

3.4. A case study: the ER glacier

3.4.1. Calculating the sensitivity of snow albedo to LACs.

We sampled fresh snow from the ER glacier in April and May of 2007 and measured the BC and dust concentrations (BCC
Figure 5. Ten year daily average albedos (blue dots with black circles) (in %), the monthly running averages (blue curves), the uncertainties (red curves with light blue shadow), and the simulated pristine snow albedos (orange dashed curves) for the investigated glaciers.

and DC) in the samples. We then used the measured data to test the albedo perturbation caused by LACs in the snow. An inverse relationship was observed between the albedo and the amount of LACs, as shown in figure 8. When the amount of LACs decreased by 4.6 ppbw d$^{-1}$ for BC and 0.855 ppmw d$^{-1}$ for dust, the albedo increased by 0.61% d$^{-1}$. 
The mean albedo observed by MODIS for the ER grid during the sampling period was 0.706. The mean annual snow density was assumed to be $\sim 480$ kg m$^{-3}$, as suggested by an earlier investigation (Zhang et al 2004). April to May is usually the melting season of the ER glacier (Hou et al 2003). We assumed a snow grain effective radius of $\sim 500$ $\mu$m.
Figure 7. Enhanced solar radiation absorption (forcing) (in W m\(^{-2}\)) in post-deposition snow at eleven glaciers and the mean forcings (in W m\(^{-2}\)) (bottom left bar charts).

which is the median of the snow grain radius when the snow transforms from new/dry to old/wet (Wakahama 1974, Kawashima and Yamada 1997).

We attributed the increase in the albedo to three factors: BCC decline, DC decline and others. The following assumption can be used to describe the factors that affect the albedo: \( \Delta(\alpha_{\text{total}}) \uparrow = \Delta(\alpha_{\text{BC}}) \uparrow + \Delta(\alpha_{\text{dust}}) \uparrow + \Delta(\alpha_{\text{others}}) \uparrow \), where \( \Delta(\alpha_x) \) refers to the albedo increase associated with a certain factor. The online version of the SNICAR model was run by inputting the concentrations of
LACs, the snow density and the grain size and using other default parameter settings (Flanner 2007). The calculated mean albedo during the sampling period was 0.707, with a difference of 0.001 from that observed by satellite. The results showed that the snow albedo was sensitive to BC and dust because more than 30% of the albedo variation could be attributed to LACs (figure 9).

3.4.2. Possible factors that lead to declines in albedo. The SNICAR model and the measured LAC data for the ER glacier can help to distinguish the effects of the factors mentioned above on the albedo. Another simulation was performed to determine how much of the albedo decline was due to BC, dust and natural aging (figure 10). The modeling results showed that the decline in LACs was responsible for 34% of the albedo variation, where BC and dust accounted for 21% and 13%, respectively, of the decline. The likely cause of the remaining 66% is the more frequent precipitation that occurs when the season transitions from dry to wet, which could cause the snow surface to become brighter.

Figure 8. Measured concentrations of LAC (BC and dust) from the collected snow samples and the satellite albedos for the upper area of the ER glacier from April to May of 2007. The dashed lines are the trends.

Figure 9. Simulated snow albedo perturbation for the ER glacier when the concentration of LACs varies from its mean to the one day lapse. The satellite albedo was sensitive to BC and dust concentrations, which could be responsible for approximately 1/3 of the albedo difference.
3.5. Estimating the impact of LAC deposition on the melting of Himalayan glaciers

We focused on the impact of LACs on the investigated glaciers to test the maintenance of the glacier area as a result of LACs. Some parameters, such as the snow temperature and heat capacity, were crucial for calculating potential melting. Meteorological observations were performed at the ER glacier from 2005 to 2008, during which the air temperature was measured (Yang et al. 2008). The annual mean air temperature above the snow surface of the ER glacier was $-11.3\, ^{\circ}\text{C}$. We used the lapse rate of $6.49\, ^{\circ}\text{C} \, \text{km}^{-1}$ recommended by the International Civil Aviation Organization (ICAO 1993) to estimate the air temperatures at the other sites. The annual mean surface air temperatures at the other sites were calculated based on their elevations and are presented in Table 3. The equation used to calculate the surface air temperatures was

$$ T_x = T_{\text{ER}} + \frac{(H_{\text{ER}} - H_x)}{1000} \times 6.49, \quad (1) $$

where $T_x$ is the surface air temperature at site $x$, $T_{\text{ER}}$ is the surface air temperature at the ER glacier, $H_{\text{ER}}$ is the elevation of the ER glacier, $H_x$ is the elevation of site $x$, and $6.49\, ^{\circ}\text{C} \, \text{km}^{-1}$ is the lapse rate.

Snow melting involves two processes. First, the snow surface temperature rises to the melting point ($0\, ^{\circ}\text{C}$), and second, the snow becomes liquid water while remaining at

the melting point. The annual mean snow temperatures at the glacial sites were derived from a linear equation (Table 3):

$$ T_s = 0.48T_a - 3.30, \quad (2) $$

Figure 10. Simulated snow albedos of the ER glacier for the following snow scenarios: pristine, aged pure, mixed with dust, mixed with BC, and observed. LACs could be responsible for approximately 40% of the decline from the albedo of pristine snow to the observed albedo during the sampling period.

Figure 11. Linear relationship between the surface air and snow temperatures derived from an in situ measurement in a N–W Himalayan snow field (Datt et al. 2008).
Figure 12. Potential contribution of shortwave radiation absorption to melting (blue bars) for the upper areas of the investigated glaciers and the $h/f$ index (red bars) criteria. The glaciers on the northern slopes are absorbing more radiation to cause mass loss than those on the southern slopes, and the middle section is safer for glaciers than other areas in the mid-Himalaya. ‘Yes’ and ‘No’ mean that ‘melting’ and ‘no melting’ occurred in the upper areas of the glaciers, respectively.

Table 3. Estimated air and surface snow temperatures in Himalayan glaciers derived from the in situ measurements on the ER glacier.

| Site ID | Elevation (m) | Measured $T_a$ ($^\circ$C) | Lapse rate ($^\circ$C km$^{-1}$) | Estimated $T_a$ ($^\circ$C) | Estimated $T_s$ ($^\circ$C) |
|---------|---------------|-----------------------------|---------------------------------|-----------------------------|-----------------------------|
| ER      | 6517          | −11.30                      | 6.49                            | −8.72                       | −6.65                       |
| NM      | 5850          | —                           | —                               | —                           | −6.97                       |
| GM      | 5561          | —                           | —                               | −5.10                       | −5.75                       |
| KW      | 6000          | —                           | —                               | −7.94                       | −7.11                       |
| QY      | 5400          | —                           | —                               | −4.05                       | −5.24                       |
| PT1     | 4876          | —                           | —                               | −0.65                       | −3.61                       |
| PT2     | 4951          | —                           | —                               | −1.14                       | −3.85                       |
| PT3     | 5351          | —                           | —                               | −3.73                       | −5.09                       |
| PT4     | 5784          | —                           | —                               | −6.54                       | −6.44                       |
| PT5     | 5222          | —                           | —                               | −2.90                       | −4.69                       |
| PT6     | 4369          | —                           | —                               | 2.64                        | −2.03                       |

where $T_a$ is the surface air temperature and $T_s$ is the surface snow temperature (figure 11), which is based on in situ measurements at a Himalayan snow surface in the northwest (Datt et al 2008). The heating/fusion ($h/f$) ratio was defined as the daily radiation absorbed by the snow divided by the energy that was needed to completely melt the mass of the snow layer. The $h/f$ ratio was calculated as follows:

$$h/f = F t / [(\rho C_p)_s d_s |T_s|],$$

where $F$ is the mean forcing of solar absorption on the glacier surface (W m$^{-2}$), $t$ is the effective solar radiation time (s), $(\rho C_p)_s$ is the snow density multiplied by the heat capacity (690 000 J m$^{-3}$ K$^{-1}$) (Kauffman 2010), $d_s$ is the maximum snow depth to which solar radiation could penetrate and $T_s$ is the snow surface temperature ($^\circ$C). The depth to which solar radiation can penetrate into snow is typically ~20 cm, within which ~99% of the incident radiation is reflected or absorbed by ice crystals (Perovich 2007). The average daily irradiance time on the Himalayan glaciers was conservatively assumed to be ~8 h (Hua et al 2010). The areas we investigated were the upper areas of the relevant glaciers, including the flat and highest glacial regions. If the ratio is lower than 1, then only a small amount of melting is probably occurring. If the ratio is higher than 1, then high melt rates may potentially occur. For $h/f$ ratios less than 1 we could calculate the potential contribution of shortwave radiation to the mass of snow/ice
that was melted per day per square meter using the following equation:

\[ M_s = [F_l - (\rho C_p) \lambda_s |T_s|] / \lambda_f, \]

where \( M_s \) is the melted snow mass (kg) and \( \lambda_f \) is the latent heat of fusion of snow (334 000 J kg\(^{-1}\) (Kauffman 2010)).

The effect of radiation forcing or absorption due to snow aging combined with LACs on the mass balance of the Himalayan glaciers was calculated and is shown in figure 12. Our calculations showed that no significant melting is occurring on the upper areas of the ER and PT3 glaciers. However, high melt rates are potentially occurring on all of the other sites. On average, the current forcing level could cause a melting rate of \( \sim2.7\ \text{kg m}^{-2}\ \text{d}^{-1} \) (\( \sim0.9\ \text{kg m}^{-2}\ \text{d}^{-1} \) due to LAC deposition) for the upper areas of these Himalayan glaciers. The melting rate on the northern slopes was \( 3.2\ \text{kg m}^{-2}\ \text{d}^{-1} \), which is higher than the rate of \( 2.3\ \text{kg m}^{-2}\ \text{d}^{-1} \) on the southern slopes.

4. Conclusions

The Himalayan glaciers are a vital water source for the people living in South Asia and China. Against the background of global warming, the accelerated melting of most Himalayan glaciers seems to be inevitable as a result of the continuously increasing emissions of anthropogenic pollutants, including BC. The general darkening trend indicates the increasing absorption of solar radiation by snow and ice during the past decade. This phenomenon, enhanced by the deposition of LACs during the late springtime, may accelerate the melting that is primarily caused by regional warming. Our investigation may be representative of more glaciers in the mid-Himalaya region.

Acknowledgments

This work is supported by the Global Change Research Program of China (2010CB951401), the State Key Development Program for Basic Research of China (973 Program: 2007CB411503), the NSFC (40901046), the SKLCS of CAS (SKLCS-ZZ-2008-01), the CMA (GYHY201106023), and the CNCC Youth Fund (2011–2012). The measurement of BC was supervised by Helene Cachier of the LSCE-CNRS of the CNCC. The measurement of \( \alpha_{\text{slopes}} \) was 3.24 from the Rongbuk Glacier, north slope of Mt. Qomolangma (Everest), Tibet–Himal region Atmos. Environ. 37 721–9

Hua W, Dong Y and Fan G 2010 The analysis of spatial and temporal characteristics of annual sunshine duration over Qinghai-Tibet Plateau J. Mt. Sci. 25 (1) 21–30 (in Chinese) ICAO 1993 Manual of the ICAO Standard Atmosphere (Extended to 80 Kilometres (262 500 Feet)) 3rd edn (Montreal: ICAO)

Immerzeel W W, van Beek L P H and Bierkens M F P 2010 Climate change will affect the Asian water towers Science 328 1382–5

Kang S, Xu Y, You Q, Flügel W A, Pepin N and Yao T 2010 Review of climate and cryospheric change in the Tibetan Plateau Environ. Res. Lett. 5 015101

Kauffman B G 2010 The NCAR CSM Flux Coupler V4.0 User’s Guide (www.cesm.ucar.edu/models/cpl/cpl4.0/dochtml)

Kawashima K and Yamada T 1997 Experimental studies on the transformation from firn to ice in the wet-snow zone of temperate glaciers Ann. Glaciol. 24 181–5

Klein A G and Stroeve J 2002 Development and validation of a snow albedo algorithm for the MODIS instrument Ann. Glaciol. 34 45–52

Loewen M, Kang S, Armstrong D, Zhang Q, Tomy G and Wang F 2007 Atmospheric transport of mercury to the Tibetan Plateau Environ. Sci. Technol. 41 7632–8

Menon S, Koch D, Beig G, Sahu S, Fasullo J and Orlikowski D 2010 Black carbon aerosols and the third polar ice cap Atmos. Chem. Phys. 10 4559–71

Ming J, Cachier H, Xiao C, Qin D, Kang S, Hou S and Xu J 2008 Black carbon record based on a shallow Himalayan ice core and its climatic implications Atmos. Chem. Phys. 8 1343–52

Ming J, Xiao C, Cachier H, Qin D, Qin X, Li Z and Pu J 2009 Black carbon (BC) in the snow of glaciers in west China and its potential effects on albedos Atmos. Res. 92 114–23

Ming J, Zhang D, Kang S and Tian W 2007 Aerosol and fresh snow chemistry in the East Rongbuk Glacier on the northern slope of Mt. Qomolangma (Everest) J. Geophys. Res. 112 D15S07

Painter T H, Barrett A P, Landry C C, Neff J C, Cassidy M P, Lawrence C R, McBride K E and Farmer G L 2007 Impact of disturbed desert soils on duration of mountain snow cover Geophys. Res. Lett. 34 L12502

Parry M L et al 2007 Technical summary Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed M L Parry, O F Canziani, J P Palutikof, P J van der Linden and C E Hanson (Cambridge: Cambridge University Press) pp 23–78

Perovich D 2007 Light reflection and transmission by a temperate snow cover J. Glaciol. 53 201–10

Prasad A K, Yang K-H S, El-Askary H M, Kafatos M 2009 Melting of major glaciers in the western Himalayas: evidence...
of climatic changes from long term MSU derived tropospheric temperature trend (1979–2008) Ann. Geophys. 27 4505–19
Qian Y, Planner M G, Leung L R and Wang W 2011 Sensitivity studies on the impacts of Tibetan Plateau snowpack pollution on the Asian hydrological cycle and monsoon climate Atmos. Chem. Phys. 11 1929–48
Ramanathan V and Carmichael G 2008 Global and regional climate changes due to black carbon Nature Geosci. 1 221–7
Ramanathan V, Ramana M V, Roberts G, Kim D, Corrigan C, Chung C and Winker D 2007 Warming trends in Asia amplified by brown cloud solar absorption Nature 448 575–8
Riggs G A, Hall D K and Salomonson V V 2006 MODIS Snow Products User Guide to Collection 5 (http://nsidc.org/data/docs/daac/modis_v5/dorothy_snow_doc.pdf)
Shi Y (ed) 2000 Glaciers and Their Environments in China: The Present Past and Future (Beijing: Science Press) (in Chinese)
Sorman A U, Akyurek Z, Sensoy A, Sorman A A and Tekeli A E 2007 Commentary on comparison of MODIS snow cover and albedo products with ground observations over the mountainous terrain of Turkey Hydrol. Earth Syst. Sci. 11 1353–60
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 Sens. Environ. 105 155–71
Thompson L, Yao T, Mosley-Thompson E, Davis M E, Henderson K A and Lin P-N 2000 A high-resolution millennial record of the South Asian monsoon from Himalayan ice cores Science 289 1916–9
Wakahama G 1974 The role of meltwater in densification processes of snow and firm Snow Mechanics Symp. vol 114 (Grindelwald, April 1974) pp 66–72
Warren S and Wiscombe W 1980 A model for the spectral albedo of snow. II. Snow containing atmospheric aerosols J. Atmos. Sci. 37 2734–45
Wiscombe W and Warren S 1980 A model for the spectral albedo of snow. I: Pure snow J. Atmos. Sci. 37 2712–33
Xu B, Yao T, Liu X and Wang N 2006 Elemental and organic carbon measurements with a two-step heating gas chromatography system in snow samples from the Tibetan Plateau Ann. Glaciol. 43 257–62
Yang X, Qun J, Liu H and Wang S 2008 Meteorological characteristics of the East Rongbuk glacier Mt. Qomolangma Arid Meteorology 26 (4) 16–21 (in Chinese)
Yao T, Pu J, Tian L, Yang W, Duan K, Ye Q and Thompson L G 2007 Recent rapid retreat of the Naimona’nyi Glacier in southwestern Tibetan Plateau J. Glaciol. Geocryol. 29 (4) 503–8 (in Chinese)
Yasunari T J, Bonasoni P, Laj P, Fujita K, Vuillermoz E, Marinoni A, Cristofanelli P, Duchi R, Tartari G and Lau K-M 2010 Estimated impact of black carbon deposition during pre-monsoon season from Nepal Climate Observatory—pyramid data and snow albedo changes over Himalayan glaciers Atmos. Chem. Phys. 10 6603–15
Zhang D, Qin D, Hou S, Kang S and Ren J 2004 Net accumulation rate of the East Rongbuk glacier and Indian summer monsoon rainfall J. Glaciol. Geocryol. 26 (2) 129–34 (in Chinese)