Observed degree-day factors and their spatial variation on glaciers in western China

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ABSTRACT. The degree-day factor (DDF) is an important parameter for the degree-day model, which is a widely used method for ice- and snowmelt computation. Spatial variations of the DDF greatly affect the accuracy of snow- and ice-melt modelling. This study analyzes the spatial variability of DDFs obtained from observed glaciers in different regions of western China. The results clearly show that the DDF for a single glacier is subject to significant small-scale variations, and the factor for maritime glaciers is higher than that for subcontinental and extremely continental glaciers. In western China the factors increase gradually from northwest to southeast. In general, the regional patterns of DDFs are detectable on the glaciers due to the unique climatic environment and heat budget of the Tibetan Plateau and surrounding regions. Low DDFs can be expected for cold-dry areas, whereas high DDFs can be expected for warm-wet areas in western China. Depending on spatial variation of the characteristics of DDFs and the meteorological data, we can provide gridded degree-day models for non-monitored glaciers to reconstruct gridded historical glacier mass-balance series in western China.

INTRODUCTION

The meltwater derived from snow and ice plays a crucial role in the annual stream-flow of arid regions in western China (Yao and others, 2004), significantly affecting catchment hydrology by temporarily storing and releasing water on various timescales (Jansson and others, 2003). Although the melt process depends on different processes of the heat budget, snow- and ice-melt modeling using the energy-balance model is relatively complex and many climatic data are needed as input. Hence, simplifying assumptions are widely used in practical computations of snow and ice melt. The degree-day model is generally considered to be one of the simplest, yet sufficiently accurate, schemes to estimate snow and ice melt. Despite its simplicity, it has proven to be a powerful tool for melt modelling, often on a catchment scale outperforming the energy-balance model, especially in the remote high-mountain regions (US Army Corps of Engineers, 1971; Anderson, 1973; WMO, 1986; Hock, 2003, 2005).

The degree-day model depends on a relationship between ablation and air temperature that is usually expressed in the form of positive temperature. The factor of proportionality is called the degree-day factor (DDF), involving a simplification of complex processes that are more properly described by the energy balance of the glacier surface and the overlying atmospheric boundary layer. This means that the factor itself depends on the energy balance (Krenke and Khodakov, 1966; Ambach, 1988; Braithwaite, 1995). Therefore, there is a variation in DDFs resulting from the energy partitioning that varies with different climate, seasons and surfaces. Some studies suggest that spatial and temporal variations of DDFs greatly affect the accuracy of snow- and ice-melt modelling (Quick and Pipes, 1977; Braun and others, 1993; Rigaudière and others, 1995; Schreider and others, 1997; Arendt and Sharp, 1999; Hock, 2003).

In western China, however, there is little research focusing on the variability of DDFs, especially in high-mountain regions. This study provides a synthesis of the variation in DDFs essential for accurately estimating snow- or ice-melt processes, especially in the non-monitored mountain regions in western China.

DATA AND METHOD

Data collection

The 15 glaciers used in our study are located in western China (Fig. 1) and were investigated or monitored during different periods in the past (Zhang and Bai, 1980; Su and others, 1985; LIGG, 1986–93; Zhang and Zhou, 1991; Liu and others, 1992; Yao and Ageta, 1993; Li and Su, 1996; Su and others, 1998). The terminus elevations of these glaciers range from 2640 to 5450 m a.s.l.

In this study, the ablation data were measured using ablation stakes. Most of the ablation records span >1 month (Table 1), and fortunately, on most glaciers, the meteorological data were recorded over the entire period. The longest combined ablation–climate dataset is for Ürümqi glacier No. 1 (UG1; 8 years, 1986–93).

However, on four glaciers, namely Meikuang, Halong, Qirbulake and Yangbulake glaciers, there are no meteorological data. Hence, daily temperature on these glaciers was extrapolated from the closest national meteorological station using the vertical lapse rate (VLR). The distance between the glacier and the national meteorological station varied considerably, from several kilometers to a few hundred kilometers. The VLR of the different latitude and altitude zones over the Tibetan Plateau and surrounding regions can be taken from Li and others (2003) and ranges from –0.0054 to –0.006°C m^{-1}. The equilibrium-line altitude (ELA) for each of the 15 glaciers was taken from the China Glacier Inventory (CGI) and ranges from 4000 to 7000 m a.s.l. (Shi and others, 2005).

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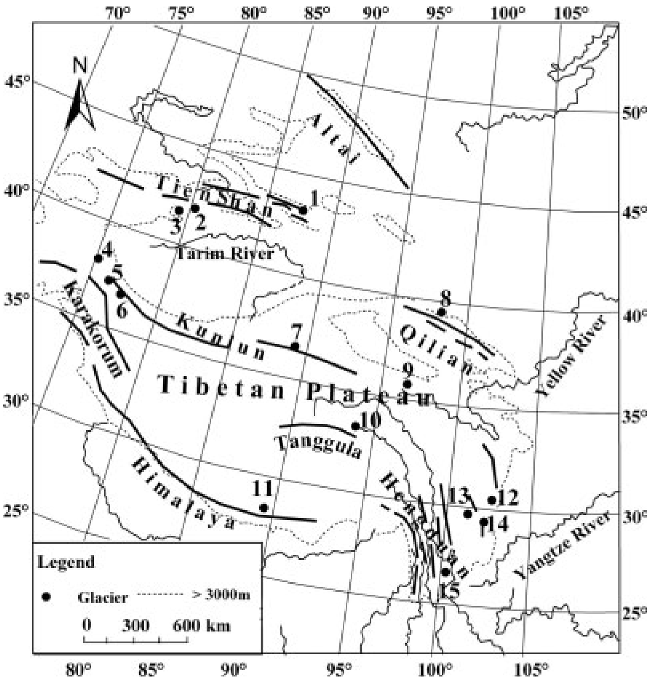

Fig. 1. Map of the study area, with locations of the 15 monitored glaciers in western China: 1. Urumqi No. 1; 2. Qiongtailan; 3. Keqicar Baqi; 4. Qirbulake; 5. Yangbulake; 6. Teram Kangri; 7. Meikuang; 8. Qiyi; 9. Halong; 10. Xiaodongkemadi; 11. Kangwure; 12. Hailuogou; 13. Dagongba; 14. Xiaogongba; 15. Baishuihe No. 1.

Method

The DDF is an important parameter for the degree-day model, which is based on a linear correlation between snow or ice melt and the sum of daily mean temperatures above the melting point during a period. Commonly, the DDF is computed either from direct measurements, using ablation stakes (e.g. Liu and others, 1996; Braithwaite and others, 1998) or snow lysimeter outflow (e.g. Kustas and others, 1994), or from melt obtained by energy-balance computations (e.g. Braithwaite, 1995; Arendt and Sharp, 1999; Zhang, 2005).

In our study, DDFs are computed from direct measurements using ablation stakes distributed on different monitored glaciers. In general, the DDF is given by

$$\mathrm{DDF} = \frac{M}{\mathrm{PDD}}, \tag{1}$$

where DDF is the degree-day factor, different for snow and ice, M is the depth of meltwater in an N day period, and PDD is the sum of daily mean air temperatures above the melting point in the same N day period. Commonly, PDD is given by (Braithwaite and Olesen, 1993)

$$\mathrm{PDD} = \sum_{t=1}^{n} H_t T_t, \tag{2}$$

where T_t is the daily mean air temperature on day t, and H_t is a logical variable, which can be defined such that $H_t = 1.0$ for $T_t \geq 0°\mathrm{C}$ and $H_t = 0.0$ for $T_t < 0°\mathrm{C}$. Strictly speaking, it might be better to define T_t as a function of a daily degree-day total, because daily mean temperatures can sometime be negative while temperatures are actually above freezing for part of the day. However, the familiar daily mean air temperature is used here for convenience in using conventional climatological data.

Based on the monitoring data of the 15 glaciers in different periods (Zhang and Bai, 1980; Su and others, 1985, 1998; LIGG, 1986–93; Zhang and Zhou, 1991; Liu and others, 1992; Yao and Ageta, 1993; Li and Su, 1996), the DDFs for ice and snow in western China can be obtained by Equations (1) and (2) (Table 1). The results reveal a large variability from site to site. The values of the factors are derived from different integration periods ranging from a few days (e.g. Dagongba glacier) to several years (e.g. UG1), which limits their direct comparison. In addition, the computed processes of DDFs involve two main sources of error:

- possible errors in measuring snow or ice melt using ablation stakes distributed on different monitored glaciers; and
- uncertainty in the VLR used to extrapolate air temperature from the nearest national meteorological station to the four glaciers where no meteorological data exist.

RESULTS

Degree-day factors

Table 1 shows that there is a large variation in DDFs, which can be attributed to the difference in relative importance of individual energy components providing energy for melt. It is generally accepted that DDFs for snow are considerably lower than those for ice, due to the higher albedo of snow compared to ice. In western China, the mean value of DDFs for ice on the monitored glaciers is $7.1\,\mathrm{mm\,d^{-1}\,°C^{-1}}$, whereas for snow it is $4.1\,\mathrm{mm\,d^{-1}\,°C^{-1}}$. So the DDF for snow reaches about 58% of that for ice in western China, while the corresponding percentage is about 40% and 70% on two Greenland glaciers and four Scandinavian glaciers (Hock, 2003).

Since the energy balance of the glacier surface varies considerably in space and time, the DDF can be expected to vary seasonally and spatially. Some studies suggest that seasonal variations in DDFs for ice tend to be less pronounced because of low seasonal variations in surface albedo (Braithwaite and Olesen, 1993). In western China, monthly variations of DDFs on Keqicar Baqi glacier, southwestern Tien Shan, given by Table 2, clearly show that monthly variations of the factor are less distinct. Similarly, seasonal variations during two summers are less pronounced over the ice on Qiongtailan glacier, which only varies from –8% to 12% (Table 3). This finding is in agreement with that of Braithwaite and Olesen (1993), who detected no evidence of distinct seasonal variation in DDFs in their analysis of 6 years of summer data over ice on Qamanârssûp sermia, Greenland. Over snow, the seasonal variation in surface albedo is more pronounced due to metamorphic evolution, so DDFs also tend to be more pronounced (Kuusisto, 1980). In this study, however, we cannot discuss the variation in DDFs for snow due to lack of the long-term monitoring data for snow in western China.

Spatial variation of degree-day factors

With different elevations, solar radiation and surfaces (albedo), DDFs will vary considerably in space. In addition, the DDF is considerably affected by the topographic effects,

Table 1. DDFs on different monitored glaciers in western China

Mountain system	Glacier	DDF_{ice} mm d^{-1} °C^{-1}	DDF_{snow} mm d^{-1} °C^{-1}	Altitude m a.s.l.	Period	Source
Tien Shan	Ürümqi No.1	8.5		3831–3945	1986–93	Liu and others (1996)
		7.3		3754–3898	1986–88	Liu and others (1996)
			3.1	4048	1986–93	Liu and others (1996)
	Keqicar Baqi	4.5		3347	28 Jun–12 Sep 2003	Zhang and others (2005)
		7.0		4216	11 Jul–13 Sep 2003	Zhang and others (2005)
	Qiongtailan	4.5		3675	17 Jun–31 Jul 1978	This study
		7.3		4100	25 Jun–14 Aug 1978	This study
		8.6		4200	21 Jun–31 Jul 1978	This study
			3.4	4400	21 Jun–11 Aug 1978	This study
Hengduan mountains	Hailuogou	5.0		3301	24 Aug 1982–Aug 1983	This study
	Baishuihe No.1	13.3		4600	23 Jun–30 Aug 1982	This study
			5.9	4800	26 Jun–11 Jul 1982	This study
	Dagongba	13.2		4540	20 Sep 1982–22 Sep 1983	This study
	Xiaogongba	12.0		4550	15 Jul 1982–15 Jul 1983	This study
Karakoram mountains	Batura	3.4		2780	Jun–Aug 1975	This study
	Teram Kangri	5.9		4630	25 Jun–7 Sep 1987	This study
		6.4		4650	24 Jun–7 Sep 1987	This study
	Qirbulake	2.6		4750	6 Jun–30 Jul 1960	This study
	Yangbulake	4.3		4800	1–5 Jul 1987	This study
Kunlun Shan	Meikuang	3.0		4840	7 May–7 Sep 1989	This study
	Halong	4.7		4616	15–28 Jun 1981	This study
		3.6		4900	14–27 Jun 1981	This study
Tanggula mountains	Xiaodongkemadi	13.8		5425–5475	Jul–Aug 1993	Kayastha and others (2003)
Qilian Shan	Qiyi	7.2		4305–4619	Jul–Aug 2002	Kayastha and others (2003)
Himalaya	Kangwure	9.0		5700–6000	20 Jul–25 Aug 1993	This study

such as slope, aspect and shape in mountain regions. Since temporal variations of DDFs on the observed glaciers of western China tend to be less pronounced, the spatial variation of the factors is discussed below.

For a single glacier, spatial variation is reflected by the relationship between the DDF and the distance between the observed site of the factor and the ELA (Figs 2 and 3). Figure 2 clearly shows that the DDFs for ice increase with decreasing distance to the ELA. It is concluded that on these monitored glaciers (Fig. 2) the larger DDFs converge at a range of 500 m which is the distance below the ELA. It is evident from Figure 2 that the DDF at higher altitude is larger than at lower altitude on these monitored glaciers where the ELA is very high (>4000 m). This characteristic can be attributed primarily to ablation due to absorbed global radiation near the ELA where the positive degree-day (PDD) is low due to low air temperature (Kayastha and others, 2003). This means that glacier melt near the ELA (with small PDD) is mainly attributed to the absorbed global radiation, which results in a larger DDF at higher altitudes than at lower altitudes, called 'the low-temperature effect' (Braithwaite, 1995). Nevertheless, an opposite trend of the DDF is given by Figure 3, which clearly indicates that the DDFs for ice decrease with distance to the ELA on the glaciers in the central Tibetan Plateau and the Himalaya. On these glaciers, evaporation from ice, especially sublimation, plays a major role in the heat budget. Due to the high energy consumption involved, evaporation from ice reduces considerably the energy available for melt, and thus reduces DDFs. In brief, the DDFs for a single glacier are subject to significant small-scale variations.

In western China the glaciers can be split into three types: extremely continental, subcontinental and maritime (Shi and Liu, 1999). For different glacier types, maritime glaciers are likely to have higher DDFs than subcontinental and extremely continental glaciers. The average values of DDFs for maritime, subcontinental and extremely continental glaciers are 10.9, 7.2 and 4.3 mm d^{-1} °C^{-1}, respectively. This finding is not in agreement with Hock (2003), who suggested that glaciers in maritime environments are likely to have lower

Table 2. Monthly variation of DDFs on Keqicar Baqi glacier (2003)

Altitude of site	DDF_{ice}		
	July	August	September
m a.s.l.	mm d^{-1} °C^{-1}	mm d^{-1} °C^{-1}	mm d^{-1} °C^{-1}
3620	–	6.1	6.0
3742	5.1	5.3	4.9
3870	4.6	6.4	5.9
4113	8.7	8.9	8.6

Table 3. Seasonal variation of DDFs on Qiongtailan glacier, 1977–78

Altitude of site	DDF_{ice}		Variation range
	1977	1978	
m a.s.l.	mm d^{-1} °C^{-1}	mm d^{-1} °C^{-1}	%
3675	4.9	4.5	–8
4100	6.5	7.3	12
Average	5.7	5.9	4

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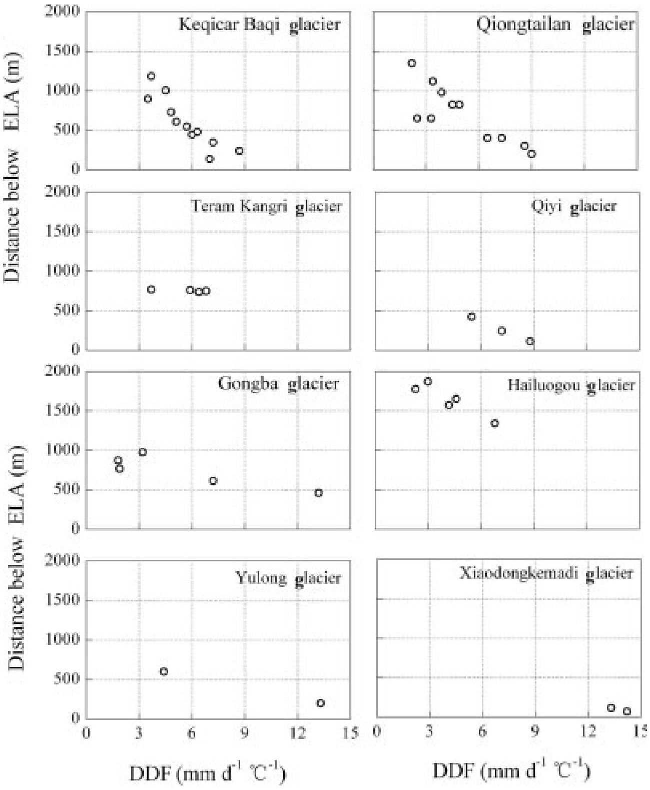

Fig. 2. Increasing variations of the DDFs with decreasing distance to the ELA in western China.

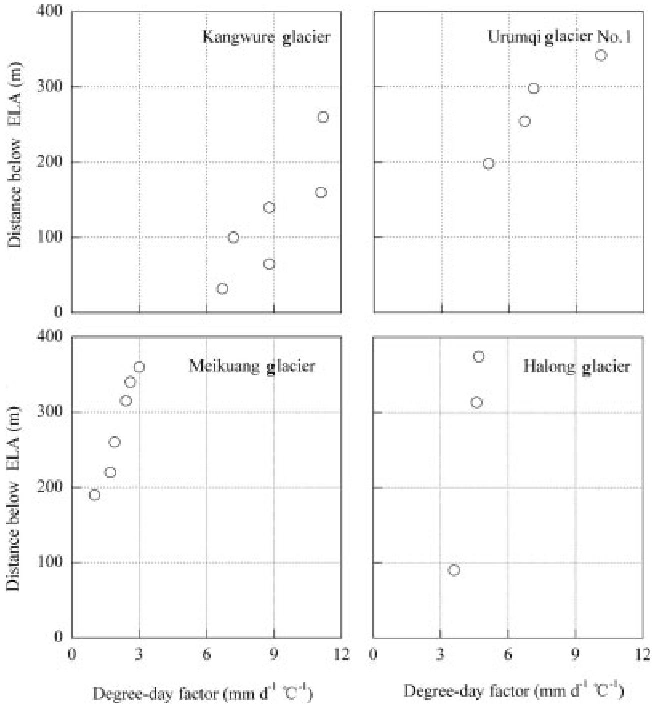

Fig. 3. Decreasing variations of DDFs with decreasing distance to the ELA in western China.

DDFs than those in more continental climate regions due to relatively large turbulent fluxes, including condensation. Although the turbulent fluxes on maritime glaciers in western China account for >50% of the heat budget in the melt season (Xie, 1994), DDFs of maritime glaciers are higher than those of subcontinental and extremely continental glaciers. Besides the influence of different regional climate conditions, the fact that the ablation area of maritime glaciers in western China is generally covered with a thin debris layer that accelerates glacier melt (Østrem, 1959; Rana and others, 1997; Zhang and others, 2005) should be emphasized among the most important reasons for this phenomenon. This debris layer has a strong influence on the surface energy balance and melting of the underlying ice, and the thermal conductivity and albedo are the main physical characteristics of a debris layer that control heat conduction to the ice–debris interface.

For the total glacier system of western China, regional patterns of DDFs are clearly detectable (Fig. 4). Figure 4 is a map of isolines for the DDFs for ice, which clearly shows that the factors increase gradually from northwest to southeast in western China. According to the DDF values, we can split the observed glaciers in western China into three categories: a high-value region (≥9.0 mm d^{-1} °C^{-1}), a mid-value region (6.0–9.0 mm d^{-1} °C^{-1}) and a low-value region (≤6.0 mm d^{-1} °C^{-1}) (Fig. 4). It is evident that the high-value region is located in the southeast of western China, whereas the low-value region lies in the northwest of western China. This distinct spatial variation of DDFs can mainly be attributed to the unique climatic environment and heat budget of the Tibetan Plateau and the surrounding regions.

Like the variation of DDFs, from northwest to southeast in western China, the climatic environment varies gradually from cold-dry to warm-wet, while the type of heat budget varies from evaporation type to condensation–evaporation type (Shi and others, 2000). This shows that regional climate conditions greatly affect the spatial variation of DDFs in western China. Generally speaking, low DDFs can be expected for cold-dry areas where available ablation energy may be mainly consumed by evaporation, especially sublimation; whereas high DDFs can be expected for warm-wet areas where the available ablation energy is mainly consumed by melting.

CONCLUSIONS

This study analyzes the spatial variation features of DDFs obtained from the investigated or monitored glaciers of western China over different periods. The mean value of DDFs for ice and snow is 7.1 and 4.1 mm d^{-1} °C^{-1}, respectively. Although temporal variations of DDFs are less pronounced, their spatial variations are significant. On a single glacier, DDFs are subject to significant small-scale variation. Considering different types of glaciers, maritime glaciers are likely to have higher DDFs than subcontinental and extremely continental glaciers. For the total glacier system, the regional patterns are detectable and significantly linked to the unique climatic environment and heat budget of the Tibetan Plateau and surrounding regions. In western China the high-value DDF region (≥9.0 mm d^{-1} °C^{-1}) is located in the southeast, whereas the low-value DDF region (≤6.0 mm d^{-1} °C^{-1}) lies in the northwest; that is, the DDFs increase gradually from northwest to southeast in western China. Generally speaking, low DDFs can be expected for cold-dry areas where sublimation plays a major role in the available ablation energy, whereas high DDFs can be expected for warm-wet areas.

This paper describes the characteristics of the spatial variation of DDFs for degree-day models, used to estimate

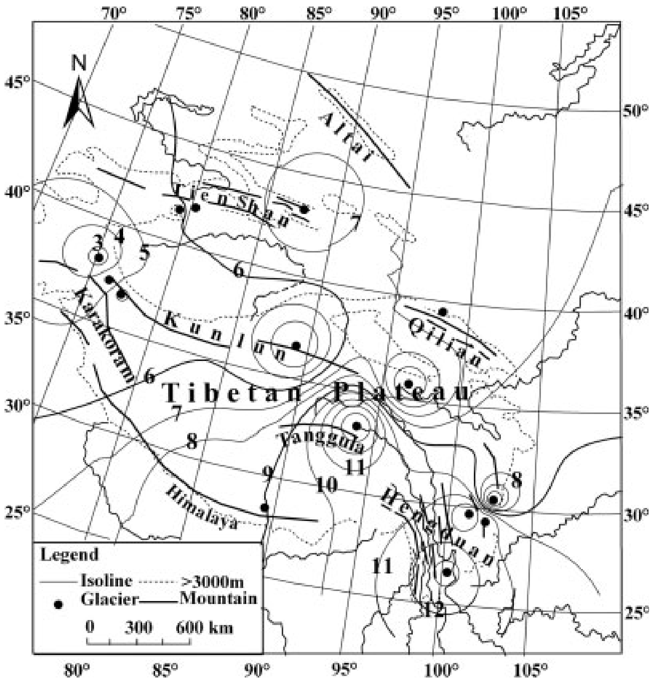

Fig. 4. Map of DDF isolines for ice in western China.

glacier melt on observed glaciers in western China. According to the CGI, there are 46 342 glaciers with a total area and volume of 59 415 km^2 and 5601 km^3, respectively, in western China. Due to the lack of money and time to monitor every glacier, only 15 glaciers have been investigated or monitored during different periods in the past. The monitoring data of the 15 investigated or monitored glaciers are of vital importance for studying the change of non-monitored glaciers in China. Hence, based on the spatial variations of DDFs and the meteorological data of different observed glaciers in different periods, we can provide gridded degree-day models of the non-monitored glaciers for reconstructing gridded historical mass-balance series in the different regions, which can then be used to predict the influence of glacier change on the water resources in western China.

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