Estimation on the response of glaciers in China to the global warming in the 21st century

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Abstract Glaciers in China can be categorized into 3 types, i.e. the maritime (temperate) type, sub-continental (sub-polar) type and extreme continental (polar) type, which take 22%, 46% and 32% of the total existing glacier area (59 406 km^2) respectively. Researches indicate that glaciers of the three types show different response patterns to the global warming. Since the Maxima of the Little Ice Age (the 17th century), air temperature has risen at a magnitude of 1.3°C on average and the glacier area decreased corresponds to 20% of the present total glacier area in western China. It is estimated that air temperature rise in the 2030s, 2070s and 2100s will be of the order of 0.4—1.2, 1.2—2.7 and 2.1—4.0 K in western China. With these scenarios, glaciers in China will suffer from further shrinkage by 12%, 28% and 45% by the 2030s, 2070s and 2100s. The uncertainties may account for 30%—67% in 2100 in China.

Keywords: modern glacier, global warming, Little Ice Age, glacier type, temperature rise in the 21st century, estimated glacier shrinkage.

Alpine glaciers are one of key indicators of climatic change, because of their sensitive response to climatic variations. An experimental study by Oerlemans (1994) demonstrates that worldwide glacier retreat during 1884—1978 corresponds to a global warming by (0.66±0.1) K in the last century[1]. He and Fortuin's (1992) further estimate showed that alpine glaciers in the world would lose their area by 1/3 to 1/2 comparing to their present extent[2]. Recent accomplishment of the compilation of Chinese glacier inventories indicates that the total glacier area and volume amount to 59 406 km^2 and 5 590 km^3. As the precious water resource, or the so-called "solid reservoir", these glaciers, most of which were distributed at the source areas of Chinese great rivers, play an important role in the economic development in western China. Due to the global warming induced by the increase of major greenhouse gases (e.g. CO_2 and others) and the accelerated melting rate of glaciers and ice caps, it is indispensable to make a suitable estimate of the glacier shrinkage during the next century.

1 An estimate of warming and glacier shrinkage in the alpine regions of western China since the Maxima of the Little Ice Age

The Little Ice Age is referred to a relatively cold period during the 15th to 19th century around the world. During this period, there have occurred three colder time intervals, which resulted in the advances of alpine glaciers and 3 obvious end moraines have been formed. These end moraines can be identified on the aerial photograph based, large-scale topographical maps, from which the glacier dimensions in each colder time intervals can be decided. The onset time of the three colder events can be estimated based on information from ice cores and tree-ring records. Of the three colder events, the second one that occurred in the 17th century is extremely cold, which is thought to be related to the minimum solar irradiance known as Maunder Minima during 1645—1715. The moraine formed during the second colder event usually overlapped on the one formed in the first colder event. Various information, such as tree-ring index at the source area of the Urumqi River[3] and at Xiaozhongdian, Diqin Prefecture of Yunan Province[6], ice core records from Dunde[4] and Guliya[5] Ice Caps, as well as snowline variations in Mt. Namjabarwa [7] leads us conclude that air temperature in western China during the 17th century was about 1.3 K on average lower than its present one. Two records in southeastern Tibetan Plateau of maritime (temperate) glaciers indicate a 0.8 K colder in the 17th century than the present. Much colder than 2.0 K in that century is found in the northwestern part of the

Plateau with extreme continental glaciers, as indicated by ice core records in the Guliya Ice Cap. In-between the two regions where subcontinental glaciers are developed, records demonstrate the 17th century temperature is about 1.4K lower than the present. However, the estimate of Jones et al. shows a worldwide temperature decrease in the same period is 0.5—0.8K, which is just half of that occurring in western China[8].

Researchers have selected well-studied mountain ranges with obvious end moraines formed in the Little Ice Age, then measured the corresponding glacier area and calculated the proportion to its present one. Because of the difference in glacier samples and the corresponding sampling mountain ranges by different researchers, the derived results are to a certain extent different from each other. By sumarizing the results of former researchers, i.e. Su and Pu[9] for the ten ranges in the Tibetan Plateau, Zhang and Wang[3] as well as Liu1) for the Tianshan and Altay Mountains, and by zoning of the three glacier types (maritime, subcontinental and extreme continental glaciers) and their relevant glacier areas at the present time, we find that glaciers in the three zones during the Maxima of the Little Ice Age were about 29%, 23% and 10% larger than that of the present glacier areas respectively.

2 Characteristics and zonal distribution of glaciers in China and their sensitivities to climate changes

The categorization of the above-mentioned three glacial types is mainly based on climatic settings, especially the regional differences in precipitation distribution. The zonal distribution of the three glacial types is shown in fig. 1.

(i) Maritime (temperate) glaciers. Glaciers with temperate characteristics are mainly distributed in the Hengduan Mts. in the southeastern part of the Qinghai-Xizang (Tibet) Plateau, including the eastern Himalayas and the mid-east section of Nyainqentanglha Mts. These glaciers have an area of about 13 200 km^2 at present, about 22% of the total glacial area in China. Summer monsoon can transport abundant precipitation to these regions with an annual sum amounting to 1 000—3 000 mm. The equilibrium line altitude (ELA) of most glaciers are quite lower, where the summer mean air temperature is higher, about 1—5℃, so that the ice temperature within the whole ice layer of most glaciers is higher than -1℃ and usually lower than 0℃ in some sections. These glaciers are so sensitive to climate changes that a small rise in air temperature can result in a larger uplift in ELA and larger shrinkage in glacier area. For example, the rise in air temperature by 1 K could result in an up shrift of about 153 m in ELA on Glacier AX010 at the southern slope of mid Himalayas[11]. In this region, air temperature has risen to 0.8 K on average since the Maxima of the Little Ice Age and the glacier area has decreased by 3 700 km^2, which corresponds to 29% of the area of existing glaciers. Glaciers of this type are less sensitive to the precipitation changes.

(ii) Subcontinental (subpolar) glaciers. Such kind of glaciers are mainly distributed in mountain ranges of Altay, Tianshan, mid to east of Qilian, eastern Kunlun and Tanggula, western Nyainqentanglha, northern slope of mid to western Himalayas and Karakorum in China. In glaciated regions, annual precipitation ranges from 500 to 1 000 mm and annual average air temperature at ELA is about -6— -12℃ with summer mean between 0 and 3℃. Most glaciers have an ice temperature of -1—-10℃ within the upper 20 m ice layer. Taking Glacier No.1 at the Urumqi Riverhead as an example, 1 K temperature rise could bring about an uplift in ELA by 86 m and the lowering by 29 m in ELA could be caused by a 100-mm increase in precipitation[10]. Glacier area of this type is at present about 27 200 km^2, 46% of the total glacial area in China. Since the Maxima of the Little Ice Age, about 6 000 km^2 in total of the glacial area has been lost, which is 23% of its present one.

(iii) Extremely continental (polar) glaciers. This type of glaciers, about 19 000 km^2 for existing glaciers (taking 32% of the total glacial area in China), are developed mainly in the western part of the Tibetan Plateau, including the western Kunlun Mts., the Qiangtang Plateau, eastern Pamir, western

1) Liu Chaohai, Glacier water resoruces and their variations in the arid northwestern China, On the Variations of Ice and Snow Water Resources, the Discharge of River Outlet and Their Forecast, printed by Lanzhou Institute of Glaciology and Geocryolgy, Chinese Academy of Sciences, 1999, 244—271.

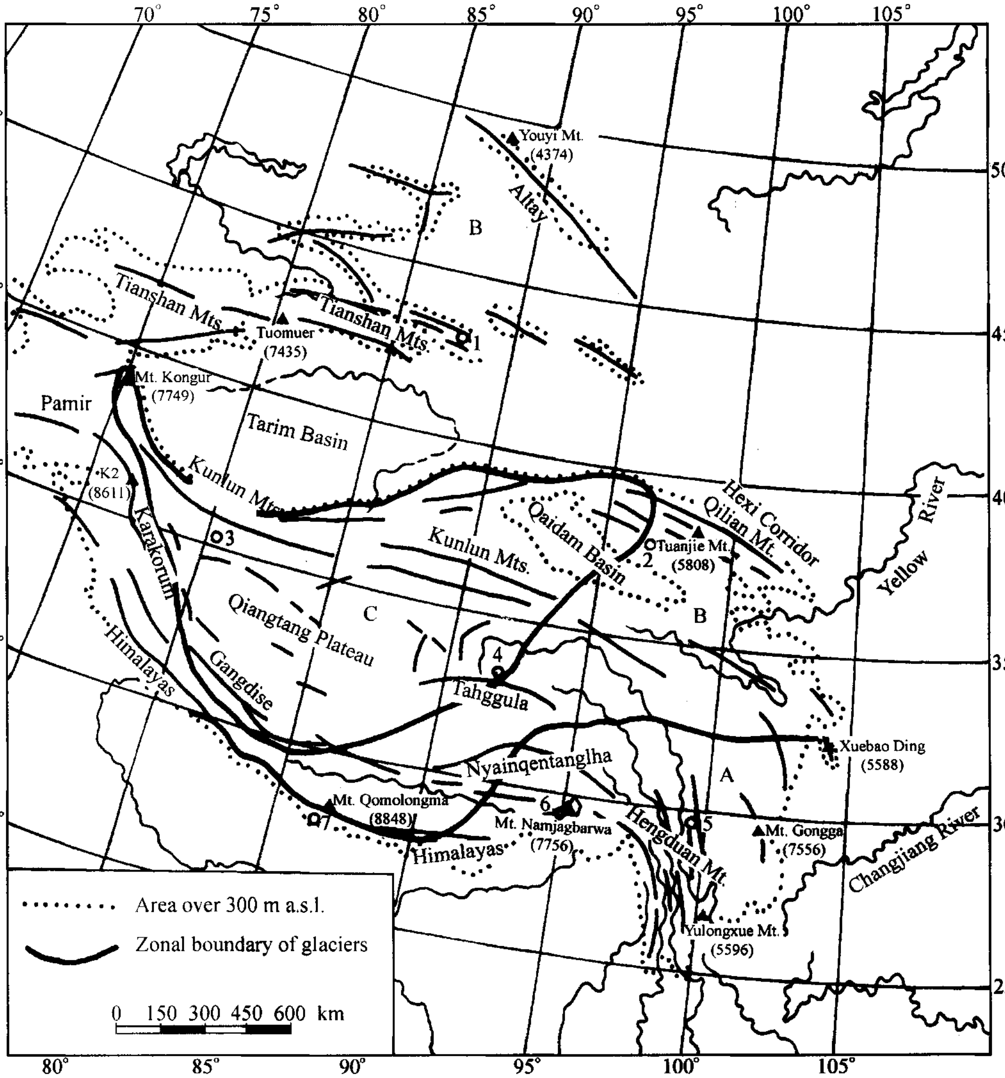

Fig. 1. A real distribution of 3 glacial types and some investigative locations. A, Maritime (temperate) glaciers; B, subcontinental (subpolar) glaciers; C, extreme continental (polar) glaciers. 1, Glacier No.1 of the Urumqi River; 2, Dunde Ice Cap; 3, Guliya Ice Cap; 4, Dongkemadi Glacier; 5, tree rings at Xiaozhongdian; 6, Glacier of Mt. Namjagbarwa; 7, Glacier AX010.

sections of Tanggula, Gangdise and Qilian Mts. The annual precipitation in the glaciated area is in the range of 200—500 mm, and the annual and summer mean air temperatures at ELA are estimated at −10 ℃ (the ice temperature at 10 m depth in Guliya Ice Cap was measured to be −19℃) and <−1℃. In such an extremely cold and dry condition, most of energy is expensed by the evaporation process on the glacier surface, so the ablation is very weak. Besides, the basal layer of glaciers is usually frozen to the bedrock and ice flows slowly. This kind of glaciers is insensitive to climatic warming, for example, 1 K air temperature rise could only result in the uplift of ELA by 58 m on Xiaodongkemadi Glacier in the Tanggula Mts.[10]. In the regions with extremely continental glaciers developed, glacier area decreased since the Maxima of the Little Ice Age only takes 10% of its existing glacial area, although air temperature has increased by 2 K.

3 Climatic Scenarios in the 21st century

The 1995 report of the Intergovernmental Panel on Climate Change (IPCC) gives a best estimate that the average air temperature around the world in 2100 will have a 2 K rise compared to the worldwide average temperature during 1961 and 1990. Such an estimate is based on various modeling results that the warming effect of the emission of greenhouse gases and the cooling effect of the emitted aerosols have been considered. However, there exist uncertainties in a range of 1—3.5 K[11] in the temperature prediction. The comparison of historical records shows that the magnitude in temperature rise on the Tibetan Plateau and northern China is larger than the mean rise in the Northern Hemisphere. In the 1980s, the mean temperature rise in the Northern Hemisphere is of the order of 0.4 K compared with that in the 1960s[12]. However, air temperatures have risen by over 0.5K on the Tibetan Plateau (0.8 K from Lhasa record and 1.0 K in the Naqu record)[13], and 1.1—1.6 K in northern Xinjiang and the Qaidam Basin[14] in the same decade. From ice core records in the Tanggula Mts. and the Guliya Ice Cap, the temperature rise is more evident; the mean temperature in the 1990s was about 1.8 and 3.3 K higher than that in the 1970s[15]. Such a higher rising amplitude of air temperature in western China since the Maxima of the Little Ice Age is not a solitary phenomenon. We can find similar patterns in the Tibetan Plateau and northern China in the period of 6—7 kaBP, when the mean temperature was about 3—4 K higher than the present average. But researches show that mean air temperature is only about 1.5 K higher than the present in the Northern Hemisphere during the same period as derived by Frenzel[16]. It is undoubted that the Tibetan Plateau and northern China would see much higher temperature rise in the 21st century than the predicted global ones by the IPCC 1995 Report. Possibly, temperature rise of 3 K can be expected in these regions.

HadCM2, a recent generation of GCMs (general circulation models), designed by the Hadley Centre of Climatic Research Unit, UK, has been used to simulate the variation processes in air temperature and precipitation of the world. The HadCM2 predicted that temperature rise would be about 3 K on the Tibetan Plateau by the end of 21st century, as we have expected. By using the model output of HadCM2 (i.e. HadCM2GSa1) and considering the above-mentioned zonal distribution of three glacial types, we make a rough estimation about the temperature rise in the 2030s, 2070s and 2100s within the three glacial zones as shown in table 1.

Table 1 Amplitude of temperature rise in the three glacial zones in western China (K)

Glacial type	Distribution regions	2030s	2070s	2100s
Maritime	Hengduan Mts. and southeast Tibetan Plateau	0.4	1.2	2.1
Subcontinental	northeastern part and southern margin of the Plateau, Tianshan	0.9	2.0	3.0
Extremely continental	western part of the Plateau	1.2	2.7	4.0

Global warming can enhance the evaporation on the land and the ocean surface, which, on the contrary, can increase the regional precipitation and accelerate the water cycle. However, variations in precipitation are much complicated and usually coincide with the changes of air temperature. Compared with former decades, the increase trend in precipitation in the 1980s is much evident in many places, such as the Tibetan Plateau, most regions of northern China and the high latitude of the Northern Hemisphere. However, precipitation decrease has also occurred in the tropical and subtropical regions from Africa to Indonesia[11]. In our opinion, the precipitation on the Tibetan Plateau and northern China will be in an increased trend, while the HadCM2 results indicate that precipitation will decrease in the southern part of the Plateau and northern India in the next century. This means that a lot of uncertainties exist in the prediction of precipitation variations, a quantitative estimate of precipitation in the 21st century may not be suitably given at present.

4 Large-scale shrinkage of Chinese glaciers in the 21st century and its uncertainty

According to climatic scenarios shown in table 1 and the empirical relations between glacier retreat and temperature rise since the Little Ice Age, we attempt to make a preliminary estimate of glacier shrinkage under the warming scenarios in the 21st century as shown in table 2.

There exist some uncertainties in the above estimation of glacier area and volume decrease. First, the temperature rise on the Tibetan Plateau will possibly appear between the low estimation of 2K and the high of 4.5K up to 2100. Second, the unstable precipitation increase during the next century will increase the accumulation and decrease the ablation on the major part of glaciers in China and hence, the retreat rate of glaciers may become slower. Third, the protecting effect of the thick debris cover on the ice tongue of hundred large glaciers may also weaken the retreat rate. Comprehensively considering

Table 2 Estimated decrease trend of Chinese glaciers in the 21st century

Glacier type	Region	2030s		2070s		2100s	
		temperature rise/K	decreased glacial area and volume(%)	temperature rise/K	decreased glacial area and volume (%)	temperature rise/K	decreased glacial area and volume (%)
Maritime	Hengduan Mts. and southeast Tibetan Plateau	+0.4	−14	+1.2	−43	+2.1	−75
Subcontinental	northeastern part and southern margin of the Plateau, Tianshan	+0.9	−15	+2.0	−32	3.0	−48
Extremely continental	western part of the Plateau	+1.2	−6	+2.7	−13	+4	−20
Sum or average		+0.8	−12	2.0	−28	3.0	−45

the above-mentioned uncertainties, the shrinkage of the glacial area and volume may be among 30%—67% of the present glaciers up to 2100, i.e. the area decrease between 1 800 and 40 000 km^2 and the volume loss between 1 690 and 3 760 km^3. Such a tremendous amount will surely and seriously affect the water resource in western China and small contribution to sea level rise in the future century.

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