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ON THE TEMPERATURE DISTRIBUTION OF GLACIERS IN CHINA

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ABSTRACT. To date, the temperatures of 22 glaciers in China have been measured. It is suggested that the minimum temperature at the base of the active layer in the upper part of the ablation area (T_{min}) be used as a characteristic temperature and compared with mean annual air temperature (T_a). The temperature distribution is discussed for various glaciers. Polar-type glaciers are characterized by low temperatures with $T_{min} < -10\,^\circ C$, T_{min} close to T_a, and a cold base in general; sub-polar-type glaciers with $-10\,^\circ C < T_{min} < -1.0\,^\circ C$, T_{min} higher than T_a, and a melting base are usually located beneath the middle of the ablation area; and temperate-type glaciers with $T_{min} > -1.0\,^\circ C$, certainly higher than T_a, and a sub-freezing near-surface layer in the ablation area all the year round, because the snow cover is thinner in winter.

1. INTRODUCTION

China has a large number of mountain glaciers with a total area of 58 650 km^2. Their temperature is of interest to glaciologists. Since 1959, every major investigation on glaciers has included temperature measurements, and much data has been obtained to date. The temperature measurements on glaciers in China can be divided into three periods depending on the technique of drilling and measuring. They are: (1) 1959–76, by manual drilling, drill depth not more than 10 m; measured by copper resistance thermometers, occasionally by thermistors, with an accuracy of 0.2 K or so; (2) 1977–85, a steam drill was employed and on some glaciers a depth of 30 m was reached; quartz thermometers with an accuracy of 0.05 K were used; (3) since 1986, by using a hot-water drill and ice-core auger, drill depths have exceeded 100 m, and an integrated circuit sensor with an accuracy of 0.05–0.1 K has been used. By the end of 1988, there were 22 glaciers whose temperatures had been measured (Fig. 1; Table I). A summary of the temperature distribution of various glaciers is presented in this paper.

For comparison, the mean annual air temperatures (T_a) at the equilibrium line are also presented. They are calculated on the basis of measurements at the nearest meteorological stations and on lapse rates determined by short-term measurements. A temperature jump from a non-glacierized area to a glacierized area is taken into account in the calculation. The uncertainty in air temperature is estimated to be about ±1 K.

2. THE CLASSIFICATION OF GLACIERS IN CHINA

Lai and Huang (1989, 1990) suggested a new principle on which glaciers are classified by means of glaciological indices at the equilibrium line which can be used to classify numerically the glaciers in China. The indices are T_a, the mean air temperature in summer, the annual precipitation, 16 m temperature measured in the upper part of the ablation area, and a parameter of flow velocity. A fuzzy cluster analysis was conducted, then verified by stepwise discriminatory analysis. As a result, 22 glaciers in China were classified into types I, II, III, and IV. In the fuzzy cluster analysis, types II and III are clustered together when $\lambda > 0.890$, and then clustered with type I when $\lambda > 0.878$, where λ is the cluster level. Lai and Huang (1989a) named types I, II, III, and IV polar type, extra-continental type, sub-continental type, and maritime type, respectively. Incorporating comments of some Chinese glaciologists who do not agree that polar glaciers appear in mid-latitudes, Lai and Huang (1990) changed the names of the four types to quasi-polar, sub-polar A, sub-polar B, and temperate. In this paper we name them polar type, sub-polar type, and temperate type, respectively, so as to conform more closely to western terminology (Table II). The classification principle, however, is different from Ahlmann's (1935); we add the word "type" to every term for distinction.

Stepwise discriminatory analysis (Lai and Huang, 1989, 1990) indicated that T_a, the mean air temperature in summer, and the annual precipitation at the equilibrium line are the dominant variables, but that the ice temperature was not discriminatory. Because of this lack of discrimination by the 16 m ice temperature, we do not attempt to classify the glaciers on the basis of the glacier-temperature regime, but instead limit the following discussion to the temperature distribution of various glaciers in China.

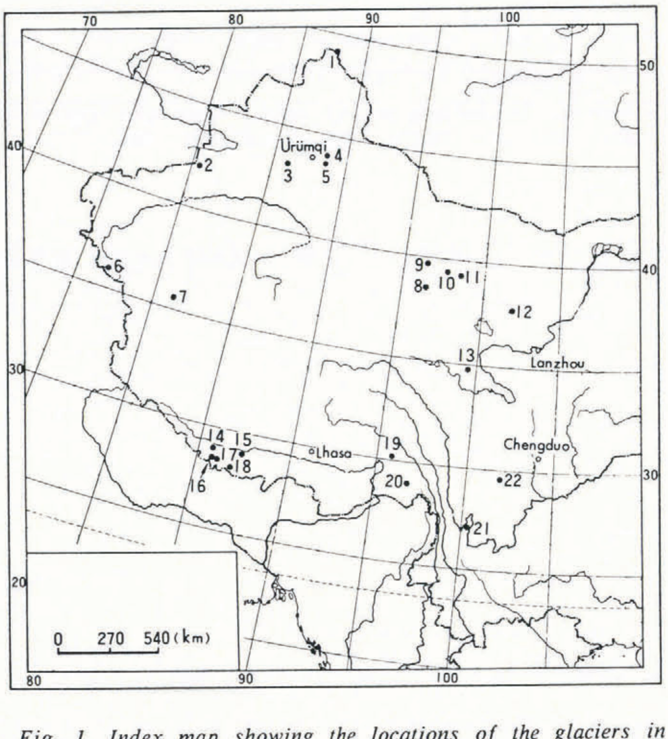

Fig. 1. Index map showing the locations of the glaciers in China whose temperatures have been measured. Glacier names are listed in Table I.

TABLE I. GLACIERS IN CHINA ON WHICH TEMPERATURE MEASUREMENTS HAVE BEEN MADE

No.	Glacier	Mountains	Length (km)	Pattern	ELA (m)	Type	Measurement year	Information source
1	Hars	Altay	10.8	Valley	3200	III	1980	Wang and others, 1983
2	West-Qiongtailan	Tian Shan	25.2	Valley	4500	III	1978	Wang and others, 1985
3	No. 1, Urumqi	Tian Shan	2.2	Cirque–valley	4030	II	1986	Cai and others, 1988
4	No. 5, Sigonghe	Tian Shan	4.4	Cirque	3900	III	1981	Ren, 1983
5	Heiguo, Bogda	Tian Shan	7.1	Valley	3900	III	1985	Personal communication from Shao W.
6	Qogir	Karakorum	21.3	Valley	5600	III	1986	Personal communication from Qin D.
7	Chongce	Kunlun	5.4	Ice cap	6000	III	1987	Shao and Liu, 1990
8	Dunde	Qilian	6.2	Flat topped	5200	I	1987	Wang, 1990
9	No. 12, Laohugou	Qilian	10.0	Valley	4700	I	1976	*
10	Qiyi	Qilian	3.5	Cirque–valley	4650	I	1975	*
11	No. 5, Yanglonghe	Qilian	2.6	Valley	4600	II	1977	Huang and others, 1982a
12	No. 4, Shuiguanhe	Qilian	2.1	Cirque	4460	II	1963	Personal communication from Cao M.
13	Halong	A'nŷemagên	8.0	Valley	4950	III	1981	Wang, 1987
14	No. 71, Poiqu	Himalaya	4.0	Valley	5640	III	1987	Liu and Sharmal, 1988
15	No. 18, Natangqu	Himalaya	3.8	Valley	5530	III	1987	Liu and Sharmal, 1988
16	Yebokangjiale	Himalaya	12.5	Valley	6000	III	1964	Huang, 1982
17	No. 7, Nakeduola	Himalaya	3.5	Flat topped	6000	III	1964	Huang, 1982
18	Rongbuk	Himalaya	22.2	Valley	5800	III	1966	Xie and Wang, 1975
19	No. 3, Guxiang	Nyainqêntanglha	1.7	Cirque	4800	IV	1965	Yuan and others, 1982
20	Azha	Gangrigabu	20.0	Valley	4600	IV	1973	Li, 1975
21	No. 1, Baishuihe	Hengduan	2.5	Cirque–valley	4700	IV	1982	Personal communication from Wang L.
22	Dagongba	Hengduan	11.0	Valley	5100	IV	1983	Personal communication from Wang L.

Glacier type is given in section 2 and Table II.
* Provided by Investigation Team on Utilization of Ice and Snow in the Qilian Shan, Lanzhou Institute Glaciology and Cryopedology, of Academia Sinica.

TABLE II. COMPARISON BETWEEN THE CHANGED CLASSIFICATION TERMS

Numerical type	*I*	*II*	*III*	*IV*
Lai and Huang (1989)	Polar	Extra-continental	Sub-continental	Maritime
		Continental		
Lai and Huang (1990)	Quasi-polar	Sub-polar A	Sub-polar B	Temperate
		Sub-polar		
This paper	Polar	Sub-polar		Temperate

3. POLAR-TYPE GLACIERS

Glaciers Nos 7–9 in Figure 1 and Table I are classified as polar type. Their T_a, annual precipitation, and mean air temperature in summer at the equilibrium line are below −12 °C, 450 mm, and −1 °C, respectively. The ice temperature is quite low and the basal temperatures are generally below the melting point.

3.1. **Chongce Ice Cap (No. 7)**

Chongce Ice Cap, 18.1 km^2 in area, was investigated by the Sino–Japanese Joint Expedition to the West Kunlun Mountains in 1987. T_a at the equilibrium line (6000 m) is estimated to be −13.4 °C, whereas the 16 m temperature was −13.2 °C (Shao and Liu, 1990). Based on a model, Zhou and Han (1990) were able to draw a graph of the two-dimensional temperature distribution as shown in Figure 2. The ice temperature is quite low and the base is entirely frozen. In Zhou and Han's (1990) model, the four measured temperature profiles shown in Figure 2 were used; in addition, heat conduction, advection and geothermal flux in the vertical direction, and internal heating were taken into account, on the asusmption that the glacier is in steady state.

3.2. **Dunde Glacier (No. 8)**

In 1987, a Sino–U.S. Joint Expedition bored holes at the summit of Dunde Glacier (5324 m), a flat-topped glacier in the Qilian Mountains with an area of 57 km^2. In one of the holes, 135 m deep, which reached the bed, a basal temperature of −4.8 °C was measured (Wang, 1990). T_a at the equilibrium line (5200 m) is estimated to be −12.8 °C.

3.3. **Glacier No. 12, Laohuguo (No. 9)**

Glacier No. 12, Laohuguo, Qilian Mountains, is a valley glacier, 10 km in length, on which temperature measurements have been made on many occasions. Its temperature is the lowest of those valley glaciers measured to date in China. In the upper part of the ablation area (4650 m, 50 m below the equilibrium line), and ice temperature of −12.8 °C was recorded at a depth of 7 m on 31 July 1976, leading to an estimate for the 16 m temperature of −10.5 °C (see section 4.5). In the middle of the ablation area, the base may locally reach the melting point. This is based on the observation that during 1960–61 the ratio of summer velocity to winter velocity was close to 1.6 near the middle of the ablation area (Huang and Sun, 1982).

4. SUB-POLAR-TYPE GLACIERS

Physically, there is no difference between type II and type III glaciers in Table II. Chinese glaciologists have, in the past, usually regarded type II as extra-continental type and type III as sub-continental type, cf. Shi and others (1988). In this paper we combine both into one type — sub-polar type.

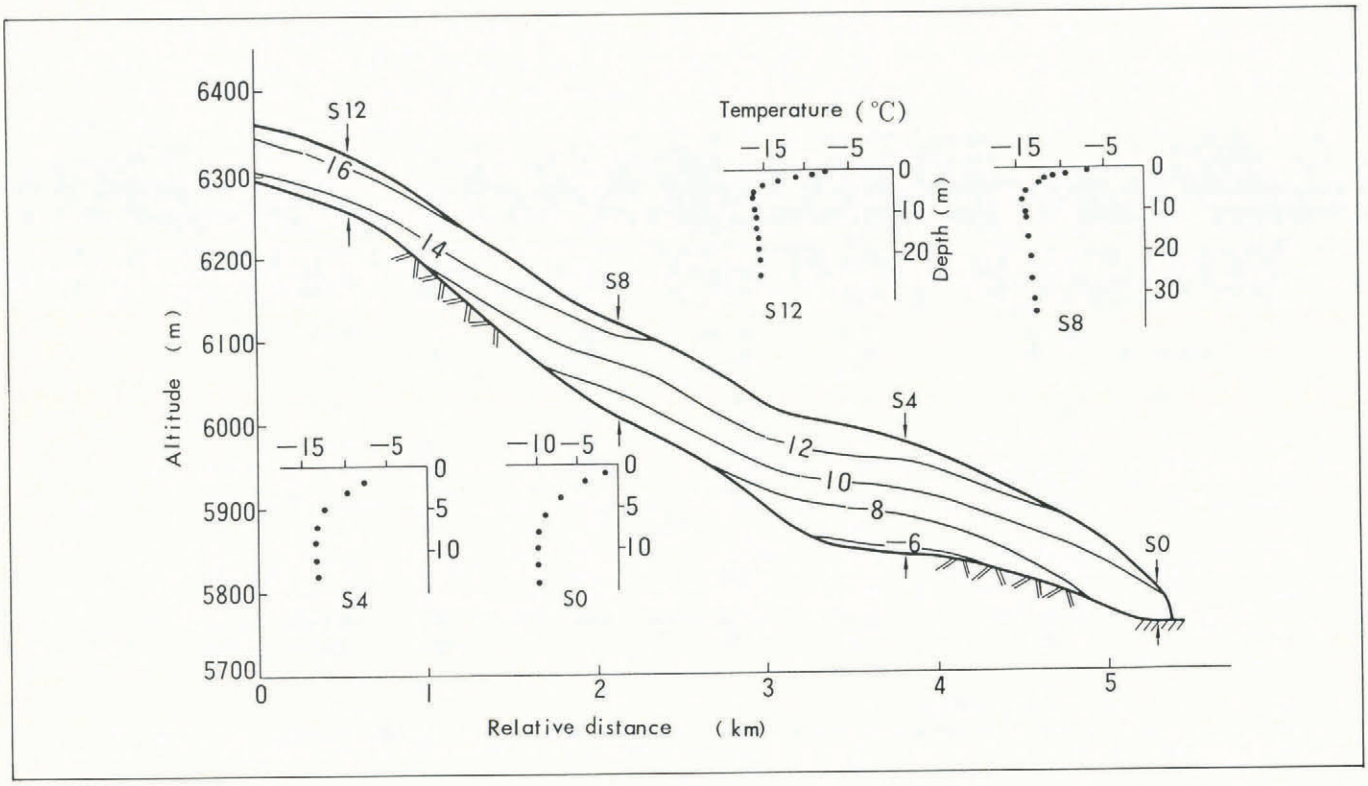

Fig. 2. Two-dimensional temperature distribution in a longitudinal profile of Chongce Ice Cap, West Kunlun Mountains (after Zhou and Han, 1990).

4.1. Temperature profile in the active layer near the equilibrium line

Modifying the solution of the equation for heat conduction in a semi-infinite medium subject to an harmonic change in surface temperature, a semi-empirical formula

$$T(y,t) = T_s \exp[-y(\omega/2k)^{\frac{1}{2}}]\sin[\omega t - y(\omega/2k)^{\frac{1}{2}}] + T_0(y) \qquad (1)$$

can be derived to describe the temperature profile in near-surface layers at or near the equilibrium line and where the surface elevation is changing only slowly (Huang and others, 1982b). In Equation (1) T_s is an apparent amplitude of surface-temperature change, t is the time, y is the distance below the surface, k is thermal diffusivity, and $\omega/2\pi$ is the frequency of the surface-temperature change. We are interested in the change with a period of 1 year, i.e. $\omega/2\pi = 1\,a^{-1}$. The equilibrium temperature $T_0(y)$ is found to change with depth and can be fitted to an empirical formula

$$T_0(y) = a_1 + a_2 \ln(y/y_0) \qquad (2)$$

where y_0 is a unit of depth (1 m), and a_1 and a_2 are constants determined by regression analysis of observations, which vary from place to place. $a_1 = T_0(y)$ when $y = 1$ m, i.e. a_1 is the equilibrium temperature at a depth of 1 m. Usually $1.2 > a_2 > 0$.

When temperature measurements are made at relatively shallow depths, say more than 5 m and less than 15 m, Equations (1) and (2) can be used to calculate the temperature at the base of the active layer at or near the equilibrium line as long as the measurements were taken at more than two different depths. For calculations, the values of T_s, a_1, and a_2 should be determined empirically. The active layer is defined as the uppermost layer of ice in which the amplitude of the annual temperature oscillation is more than 0.2 K. The thickness of the active layer is about 15–20 m.

4.2. Temperature regime in the infiltration zone

Considerable surface melting occurs in the infiltration zone of sub-polar-type glaciers during the summer. When melt water refreezes in the snow, latent heat is released, which warms the snow beneath. Percolation and refreezing become major processes of heat transfer in summer, and dominate the temperature profile of the near-surface layer in the infiltration zone all year-round. Cai and others (1986) have suggested mathematical models for calculating the water–heat transfer and the temperature profiles in this zone based on experiments and observations made on Urumqi Glacier No. 1. According to their calculations, the warming effect of melt water may reach a depth of 20 m by the end of the melt season. Measurements made in the infiltration zone of the eastern tributary of Urumqi Glacier No. 1 showed that it was 0°C in the uppermost 11 m and ⩾−0.1°C down to a depth of 30 m during 20 July–10 August 1982 (Zhang and others, 1984). Hooke and others (1983) found a similar penetration depth for this warming.

4.3. Longitudinal temperature profile

To describe quantitatively the changing temperature with elevation, Huang and others (1982a, b) have suggested that the temperature at the base of the active layer should be used. They have developed a scheme which describes its variation with elevation. Their model has been verified by measurements on Urumqi Glacier No. 1 (Fig. 3). As shown in Figure 3, the temperature at the base of the active layer decreases with increasing elevation, as does the air temperature, but in the infiltration zone there is a maximum due to the greater warming effect of refreezing melt water. The temperature at the base of the active layer decreases from this maximum both up-glacier and down-glacier. However, down-glacier a minimum value does not appear at the equilibrium line, as the model of Huang and others (1982a, b) suggests, but somewhere in the upper part of the ablation area. Because the warm ice in the infiltration zone is flowing down-glacier, it takes several years for it to be cooled. This was confirmed by measurements in deep holes in Urumqi Glacier No. 1 in 1986. Figure 4 shows the location of the holes and Figure 5 shows the temperature profiles. The profiles show that the temperature in the upper part of the ablation area (T_2) is lower than that near the equilibrium line (T_3) from the surface to a depth of 88 m (Cai and others, 1988).

The temperature at the base of the active layer of a sub-polar glacier may reach the melting point if the glacier extends to a sufficiently low elevation (Huang and others, 1982a, b; Hooke and others, 1983).

Measurements made on sub-polar glaciers show that the temperature at the base of the active layer is higher than T_a at the same elevation.

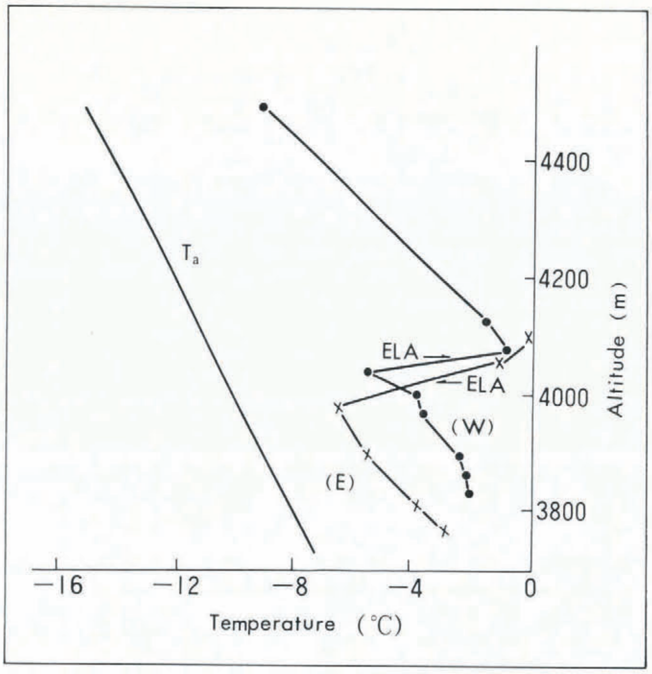

Fig. 3. Two measured temperature profiles showing how the temperature at the base of the active layer changes with altitude on Urumqi Glacier No. 1. E, east tributary; W, west tributary; ELA, equilibrium-line altitude; T_a, air temperature; at the summit it was measured at the base, 8.5 m deep, others at 16 m depth (by courtesy of Ren Jiawen).

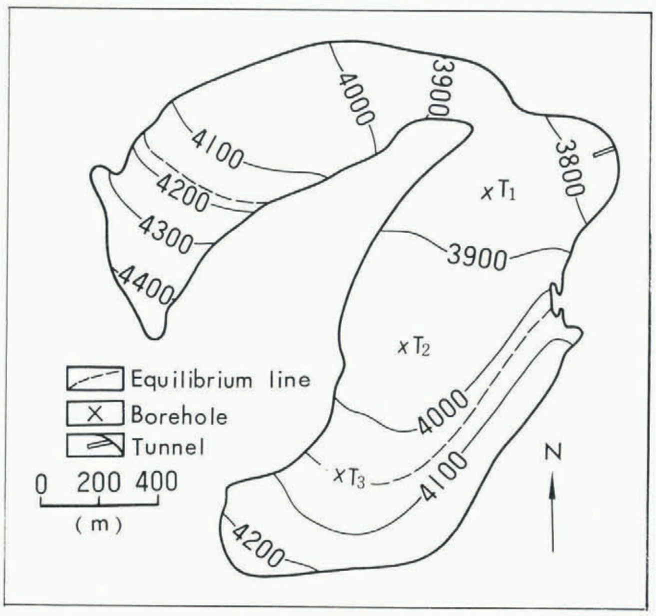

Fig. 4. A map showing the locations of holes for temperature measurement and the artificial tunnel in Urumqi Glacier No. 1.

4.4. Basal temperature

Among the sub-polar-type glaciers in China, the basal temperature has been measured only on Urumqi Glacier No. 1. It is estimated by radar sounding that the ice thicknesses at T_1, T_2, and T_3 (Figs 4 and 5) are 96, 138, and 106 m, respectively. Thus, the holes at T_3 reached and T_1 is close to the base of the glacier. Integrated-circuit sensors with an accuracy of ±0.05 K were used to measure the ice temperatures.

A temperature-distribution model based on the measurements in deep holes over a period of several months was made by Cai (unpublished). In the model, glacier flow and heat conduction in horizontal and vertical directions, and the geothermal flux are taken into consideration

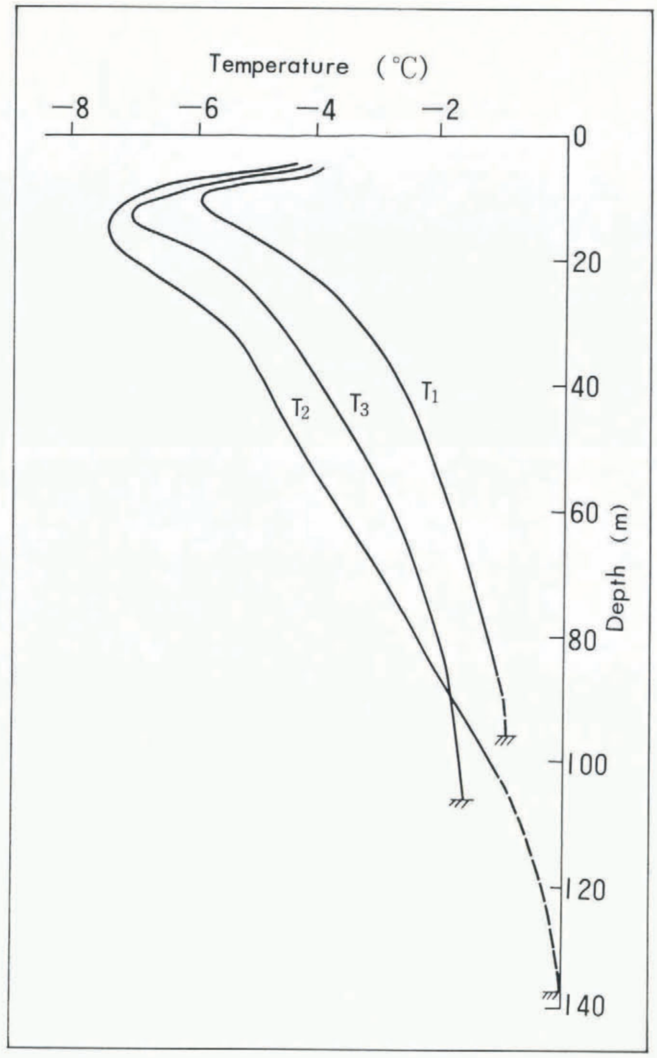

Fig. 5. Temperature profiles measured on Urumqi Glacier No. 1 on 27 September 1986. The dotted lines are extrapolated (after Cai, unpublished).

assuming that the temperature field is stable. As a result, it is found that the highest basal temperature, greater than −0.5°C, occurs in the middle of the ablation area, the thickest part of the glacier. We therefore believe that in sub-polar-type glaciers, as long as they are as large or larger than Urumqi Glacier No. 1, a small cirque-valley glacier, the base may be at the melting point at some locations.

In the terminus of Urumqi Glacier No. 1, a new tunnel (Fig. 4) was excavated in the autumn of 1988. The ice temperature was measured while the tunnel was being extended. The temperature profile is shown in Figure 6. Because the temperatures in the tunnel are below 0°C and, in view of the fact that permafrost is present in front of the glacier, the 0°C isotherm must lie at a depth of at least a few meters in the bed, as suggested by Echelmeyer and Wang (1987).

4.5. Regional features

Huang and others (1982a, b) have attempted to describe how the near-surface temperature changes with elevation using measured and calculated temperature at the base of the active layer as a temperature index of the active layer, and using the temperature at the base of the active layer at the equilibrium line as a characteristic temperature to determine the regional features of glacier temperature. As mentioned above, however, the temperature at the equilibrium line does not display significant characteristics. We prefer to take the minimum temperature at the base of the active layer in the upper part of the ablation area (T_{min}) as the characteristic temperature for a glacier. However, it is difficult to determine T_{min} owing to the

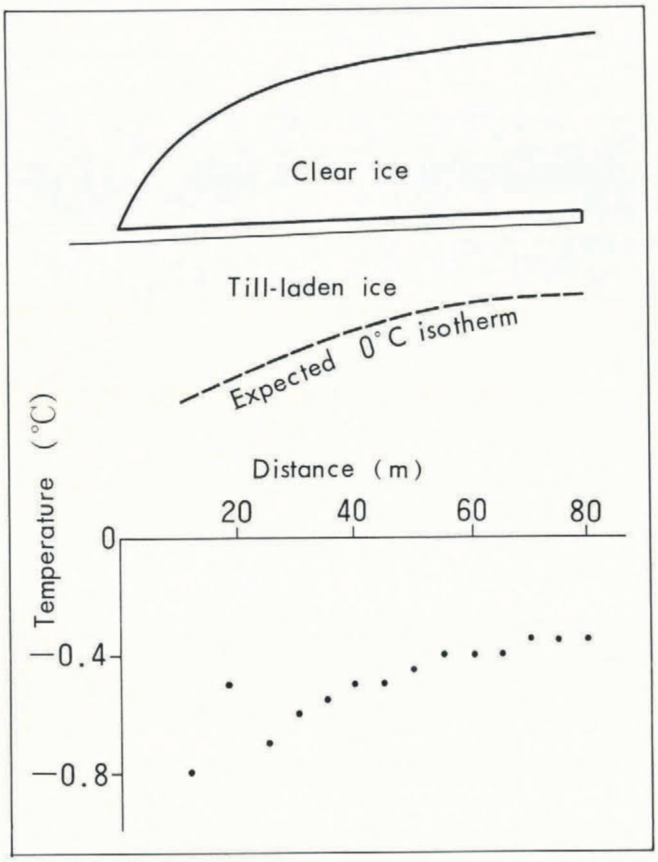

Fig. 6. Section through the tunnel in Urumqi Glacier No. 1 with its temperature profile measured during excavation in September–October 1988 (by courtesy of Zhou Tao).

spatial limitations of the measurements. Therefore, instead of T_{min}, we take a temperature at the base of the active layer measured near the equilibrium line or in the upper part of the ablation area, designated T'_{min}.

There are 14 sub-polar-type glaciers in China for which T'_{min} is known. These are listed in Table III together with the altitudes at which the measurements were made. The equilibrium-line altitudes and measurement years of the glaciers in Table III are shown in Table I. In Table III we take the 16 m temperature as the temperature at the base of the active layer. Equations (1) and (2) are used to calculate T'_{min} if the measured depth is less than 16 m. At Glacier No. 4, Shuiguanhe (No. 12), no measurement was made in the ablation area and therefore T'_{min} is not known for the glacier. The T'_{min} for Glacier Rongbuk (No. 18) in Table III is higher than it should be, as the measurement point was in the lower part of the ablation area. For comparison, estimated T_a at the measurement altitudes are also shown in Table III.

Hooke and others (1983) analysed the complex process controlling the near-surface temperature in the lower part of the accumulation area and in the ablation area on polar and sub-polar glaciers, compared the ice temperature with T_a, and pointed out that the principal controlling factors are snow-cover thickness, mean July temperature, and T_a.

From Table III we can see that T'_{min} is, without exception, a few degrees higher than T_a. T'_{min} for a flat-topped glacier, Glacier No. 7, Nakeduola (No. 17), is clearly lower than that for Yebokangjiale Glacier (No. 16), an adjacent valley glacier on the northern slope of Mount Xixiabangma. This is due to the thin snow cover on a flat-topped glacier, which reduces its winter insulating effect. Kotlyakov and Krenke (1982) have mentioned that the accumulation on a flat-topped glacier may be less, at the most 30%, than the average annual precipitation at a fixed geographic position, but on a cirque glacier it is always more than the annual precipitation. The same reasoning could explain why T'_{min} is close to T_a for Chongce Ice Cap (No. 7).

5. TEMPERATE-TYPE GLACIERS

Temperature-distribution studies on temperate-type glaciers are not as detailed as on sub-polar-type glaciers in China. Nos 19–22 in Figure 1 and Table I are temperate-type glaciers, which develop under conditions of the South Asian monsoon circulation. The precipitation on temperate-type glaciers in China is large in summer and low in winter. Therefore, the winter snow cover is not as thick as on other temperate glaciers, thus providing less insulation.

5.1. Accumulation area

In the accumulation area of temperate-type glaciers, there is no doubt that the main body of the glacier is at the melting point. The near-surface layer cools during the winter but quickly warms in summer due to melt-water percolation. A measurement made by Wang Lilun from 30 June to 11 July 1982 indicated that in the lower part of the accumulation area of Glacier No. 1, Baishuihe, a 10 m thick near-surface layer consists of firn, which is at the melting point throughout. If the maximum elevation of a temperate-type glacier were higher than the upper limit of the warm-infiltration zone (wet-snow zone), it would have a temperature distribution similar to that of the cold-infiltra-

TABLE III. 16 m TEMPERATURE MEASURED AT THE EQUILIBRIUM LINE OR IN THE UPPER PART OF THE ABLATION AREA (T'_{min}) OF SUB-POLAR-TYPE GLACIERS IN CHINA, COMPARED WITH MEAN ANNUAL AIR TEMPERATURE (T_a)

No.	*Glacier*	*Type*	*Altitude*	T'_{min}	T_a	$T'_{min} - T_a$
			m	0°C	0°C	K
1	Hars	III	3180	−3.5*	−7.3	3.8
2	West-Qiongtailan	III	4300	−3.0	−9.2	6.2
3	No. 1, Urumqi	II	4033	−7.3	−9.9	2.6
4	No. 4, Sigonghe	III	3750	−1.4*	−7.2	5.8
5	Heiguo, Bogda	III	3840	−3.6	−8.7	5.1
6	Qogir	III	5300	−4.8*	−7.8	3.0
10	Qiyi	II	4600	−9.0*	−10.5	1.5
11	No. 5, Yanglonghe	II	4648	−7.9	−11.8	3.9
13	Halong	III	4900	−6.6*	−8.3	1.7
14	No. 71, Poiqu	III	5440	−3.0*	−6.7	3.7
15	No. 18, Natangqu	III	5330	−2.9*	−6.1	3.2
16	Yebokangjiale	III	5834	−5.8*	−9.2	3.4
17	No. 7, Nakeduola	III	5900	−8.3*	−9.6	1.3
18	Rongbuk	III	5400	−1.7*	−6.5	4.8

* Calculated from shallow measurement.
Other parameters are given in Table I.

tion zone (percolation zone) of sub-polar-type glaciers. But, in the region of the temperate-type glaciers in the south-eastern Qinghai-Xizang (Tibet) Plateau of China, the maximum elevation of the glaciers is usually below 6000 m a.s.l., which is still in the warm-infiltration zone.

5.2. Ablation area

In the near-surface layer, 10 m or more thick, the temperature of temperate-type glaciers is below but close to 0 °C. Because of the thinner snow cover, the winter cold is able to penetrate deeper. But conductive warming in summer is inhibited by the fact that the ice temperature cannot exceed 0 °C. Most of the heat received at the surface is used in melting. Therefore, summer warming cannot counteract winter cooling. Thus, it is one of the features in the ablation areas of temperate-type glaciers in China that temperate ice is often covered by a sub-freezing surface layer. Figure 7 shows two temperature profiles from the ablation areas of temperate-type glaciers in China, both of which have this cold surface layer.

For temperate-type glaciers in China, T_{min} is 2.6–4.5 K higher than T_a (Lai and Huang, 1989, 1990).

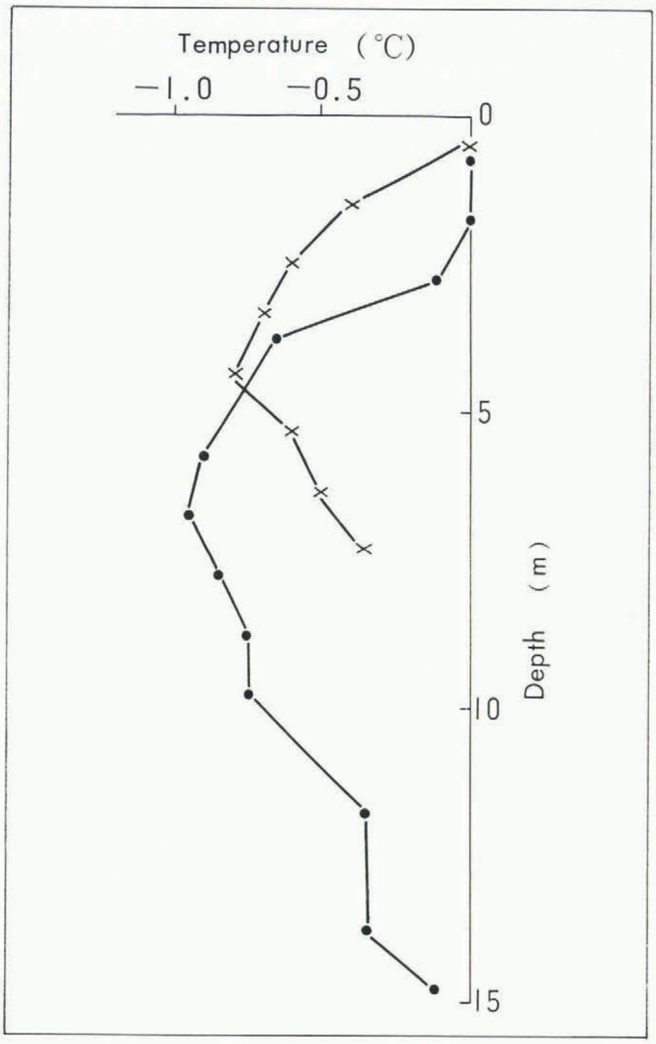

Fig. 7. Temperature profiles of two temperate-type glaciers. ×, upper part of the ablation area (4600 m) on Glacier No. 1, Baishuihe, 11 July 1982; ·, middle part of the ablation area (4540 m) on Dagongba Glacier, 30 September 1982. The glacier surface at the time of measurement is taken as the origin of the depth coordinate (by courtesy of Wang Lilun).

6. CONCLUSIONS

The minimum temperature at the base of the active layer in the upper part of the ablation area (T_{min}) can be taken as a characteristic temperature of a glacier.

The classification suggested by Lai and Huang (1989, 1990) can be regarded as a basis for discussing the temperature distribution of glaciers in China. In this classification, which is different from Ahlmann's (1935), glaciers are numerically classified by multi-factors which are measured at a fixed place — the equilibrium line. Features of the temperature distribution of glaciers in China can be summarized as follows:

1. Polar-type glaciers — low surface-layer temperature, $T_{min} < -10\,^{\circ}C$, generally with a cold base except for large valley glaciers, where part of the base in the ablation area may be at the melting point. T_{min} approximates or even equals T_a.

2. Sub-polar-type glaciers — $-10\,^{\circ}C < T_{min} < -1.0\,^{\circ}C$, usually with basal melting in the middle of the ablation area. The area of basal melting will extend to the terminus in a large valley glacier whose terminus reaches a temperate region. T_{min} is generally higher than T_a.

3. Temperate-type glaciers — the main body, including the base, is at the melting point. However, in the ablation area, the near-surface layer is below 0 °C all the year round because of a thinner winter snow cover. T_{min} is certainly higher than T_a.

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