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Climate, mass balance and glacial changes on small dome of Collins Ice Cap, King George Island, Antarctica

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Abstract During 1991/1992 Chinese Antarctic Expedition, a full-year glacial investigations on the small dome of Collins Ice Cap were carried out, the data from investigations showed that vertical temperature gradients on small dome were about 0.79℃/100m and 0.66℃/100m in the summer and in the winter separately. Lower summer temperature in this area is one of most important conditions for glacial development. In 1991/1992 the small dome was a weak positive balance year with a mass balance difference of 163 mm, annual ELA was 140m, mass balance gradient was 8.4mm/m and mass balance level was 928mm. Mass balance fluctuations on small dome in 1971 -1992 were calculated by a new method, the results revealed that the small dome of Collins Ice Cap was relatively stable over 21 years.
Key words climate, mass balance, glacial change, Collins Ice Cap, Antarctica

1 Introduction

The small dome (62°12′S, 58°57′W, 252 m a. s. l.) of Collins Ice Cap, King George Island, with 4.5 km length, 3.0 km width and 15 km^2 in area, is only about 200m away from Artigas Station (Urugauy). Its topography likes a regular dome (Fig. 1).

During the 1991/1992 Chinese Antarctic Research Expedition, one meteorological station and sections for mass balance observation were established on the small dome of Collins Ice Cap. Two times of short-term meteorological observations and a full-year mass balance measurement were carried out. In this paper, the field data were discussed, furthermore, a method was developed to recover the mass balance state of small dome in recent 21 years.

2 The significant features of glacial climate

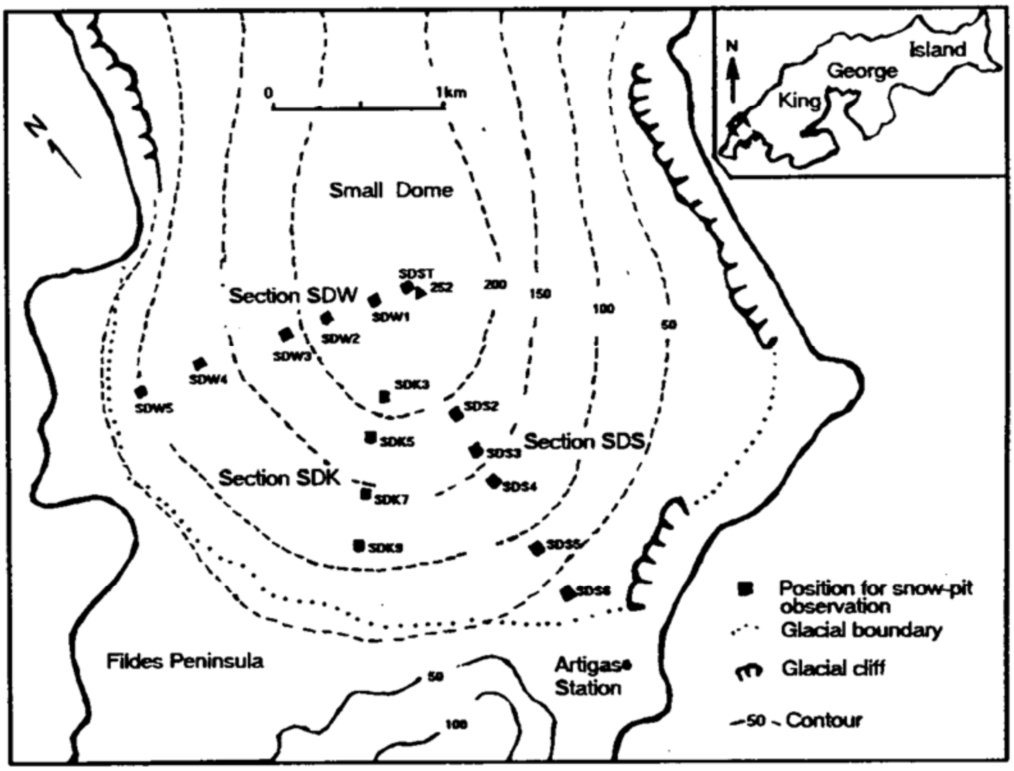

Fig. 1. Sketch map of the small dome of Collins Ice Cap.

The climate of King George Island belongs to subpolar maritime climate. According to the data(1970～1991) of Frei Meteorological Center(elevation, 10 m a. s . l.), mean annaul temperature was −2. 4℃, annual precipitation was 500 mm.

On the basis of the meteorological observations on the summit of small dome from Dec. 24, 1991 to Jan. 7, 1992 and Jun. 9 to Jul. 9, 1992, as well as meteorological data of station at the coast nearby, the vertical temperature gradients of small dome in these two periods, −0. 78℃/100m and −0. 66℃/100m were obtained, approximately representing the gradients in summer and winter respectively, which had a large difference to the data (−1. 0℃/100m) used in this area previously (Wang *et al.* , 1990; Ren, 1990).

By the use of these two temperature gradients, the temperatures at the equilibrium line altitude (ELA) were calculated. Comparing with the temperatures at ELAs of maritime or continental glaciers in West China (Table 1), we found that, owing to the small annual temperature range, mean annual temperature at ELA of small dome, −3. 5℃, is very high, but the average temperature in summer(Dec. to Feb.) is only 0. 0℃. The difference of summer mean temperature with mean annual temperature is only about the half of those in West China. Thus, although the annual precipitation is much smaller and the mean annual temperature is even higher than those of alpine maritime glaciers, the glacier can exist as the glacial ablation in summer is weaker. In addition, this climate characteristic also affects the glacial properties such as ice formation, glacial temperature.

Table 1. A comparison of temperatures and precipitations at ELAs between the small dome and alpine glaciers in West China

Glacier	ELA (m)	Mean Annual Temperature(℃)	Summer Mean Temperature(℃)	Precipitation (mm)	Source of data
Small Dome	160	−3.5	0.0	700	
Gongga glacier	4800	−4.4	3.6	2000	Su *et al.*, 1987; Pernsonal exchange
No. 1 Glacier Urumqi	4050	−10.0	−0.2	647	Ohmura *et al.*, 1992; Yang *et al.*, 1988
"July 1st" Glacier	4650	−10.0	0.0	500	Ding and Kang, 1985; Gao and Yang, 1985
No. 4 Glacier Shuiguan River	4500	−9.0	1.5	800	Ding and Kang, 1985; Gao and Yang, 1985

3 Mass balance

3.1 Observations and calculations for mass balance

Three observation sections for the mass balance measurement radiated from the summit of small dome to ice cap edge, among these, section SDS, with 5 fixed positions for snow-pit observation(Fig. 1), was the main section, which observed 9 times in the full year. Furthermore, 64 stakes were used for mass balance observation. The results of mass balance measurement at section SDS are listed in Table 2.

The correlation coefficient between net mass balances b_n(mm) of snow pits and the height differences of their mass balance stakes within each observation interval is 0.93, and the regression equation is:

$$b_n = -19 + 607.7\,H \tag{1}$$

this equation can be used to calculate net mass balances at the positions of stakes.

Generally, since the areas of the ice caps or ice sheets are much larger, their surficial mass balance are usually calculated in the drainage areas controlled by streamlines (Ageta and Kadota, 1992; Bently and Giovinetto, 1992; Noble, 1965). By the use of investigation data of glacial surface altitude and network of stakes for movement observation at section SDS, a map for streamlines of the section is drawn on the scale of one-ten thousandth. Based on the certain intervals, areas within two streamlines are measured (Table 3).

3.2 Characteristics of glacial mass balance

3.2.1 Mass balance gradient

Variations of Mass balance with altitude can be expressed by mass balance gradient (E_g):

$$E_g = \mathrm{d}b_n/\mathrm{d}H \tag{2}$$

or approximate to:

$$E_g = \Delta b_n / \Delta H \quad (3)$$

where b_n is net mass balance (mm), H is altitude(m).

From equation (3), E_g was 8.4mm/m around equilibrium line at section SDS.

Table 2. Net mass balance (mm water equivalent) of snow pits at section SDS from the end of the summer in 1990/1991 to observation dates.

Year	Date/month \ snow pits	SDST	SDS2	SDS4	SDS5	SDS6
	Altitude(m)	252	185	140	90	45
1991	3/11	665		476		
	6/11		1090			
	10/11				900	1009
	29/11			556	964	1077
	30/11	862	1178			
1992	9/1	849				
	13/1		957	470	673	629
	24/2	448	658	14		−264
	27/3		695		−139	−348
	28/3			7		
	30/3	433				
	23/5	544	860		63	−272
	24/5			169		
	27/7	664	1064	249	215	−15
	10/9	819				
	15/9				341	
	23/9		1236	401		
	8/10					583
	4/11				527	651
	7/11	988	1526	549		

Table 3. Area of each altitude interval between two flowlines at SDS section of the small dome.

Alt. int. (m)	30−50	50−80	80−110	110−140	140−170	170−200	200−230	230−252
Area (km^2)	0.082	0.103	0.115	0.121	0.125	0.112	0.083	0.078

3.2.2 Mass balance level

$$m = (\bar{c}_a + \bar{a}_a)/2 \quad (4)$$

in which

$$\bar{c}_a = \bar{c}_w + \bar{c}_s \quad (5)$$

$$\bar{a}_a = \bar{a}_w + \bar{a}_s \quad (6)$$

where, $\bar{c}_a$, $\bar{c}_w$ and $\bar{c}_s$ are the average total accumulation, average total accumulation in winter and average total accumulation in summer; $\bar{a}_a$, $\bar{a}_w$ and $\bar{a}_s$ are the average total ablation, average total ablation in winter and average total ablation in summer separately.

At section SDS, $\bar{a}_w \approx 0$ is due to quite weak glacial ablation in winter, and:

$$\bar{c}_w = \frac{1}{S} \sum_{i=1}^{n} S_i \bar{c}_{wi} \tag{7}$$

$$\bar{a}_s = \frac{1}{S} \sum_{i=1}^{n} S_i \bar{a}_{si} + \bar{c}_s \tag{8}$$

where, S is the total drainage area of the section, S_i, the drainage areas at each internal (Table 3); $\bar{c}_{wi}$ and $\bar{a}_{si}$, average net accumulations in winter and average net ablations in summer at the corresponding intervals.

The value of $\bar{c}_s$ was equal to the solid precipitation at section SDS in summer. The snow precipitation at Artigas Station was 54. 7 mm in the summer of 1991/1992, average snowfall estimated at section SDS was about 80 mm. From equations (7) and (8), $\bar{c}_w$ was 929 mm, $\bar{a}_s$, 846 mm. From equations (4), (5) and (6), mass balance level was 928 mm.

3. 2. 3 Mass balance difference

The mass balance difference at section SDS in 1991/1992: $b_n = \bar{c}_a - \bar{a}_a = 163$ mm water equivalent.

4 Glacial change

4. 1 Types of equilibrium lines and their relationships

A equilibrium line is the bounary line which divides glaciers into accumulation and ablation regions. In light of the field investigations in 1991/92, two kinds of equilibrium line altitude (ELA) could be determined.

(1) Net mass balance at snow pit SDS4 were 12 mm and 7 mm separately at the ends of February and March, so we could determine the ELA in 1991/1992 was around 140 m a. s. l. . According to the other method, we could also obtain the annual ELA was at the same altitude(Wen, *et al.* , 1994). This is the specific annual ELA, denoted by ELA_i.

(2) On the basis of glacial movement measurement, the dynamic equilibrium line was determined as 160 m a. s. l. , this line was approximate to the mean equilibrium line, denoted by ELA_a.

(3) The third equilibrium line altitude is the altutide when the whole glacier is in the condition of stable equilibrium state, denoted by ELA_0.

The relationships of three different ELAs are shown in Figure 2a. $Eg = \Delta b / \Delta H = tg\theta$. The mass balance value at ELA_0 can reflect the mass balance state of the whole glacier, it means mass balance value Δb at ELA_0 is approximate to the average mass balance value of the whole glacier (i. e. the mass balance difference b_n). When $ELA_0 > ELA_i$, The mass balance value at ELA_0 is positive, glacier is in the condition of positive mass balance, conversely, $ELA_0 < ELA_i$, glacier is in the negative state. $ELA_0 < ELA_a$, the glacier is in the period of glacial retreatment, and $ELA_0 > ELA_a$, the glacier advances. Only when $ELA_0 \approx ELA_a$, the glacier will be in the condition of stable state for a long time.

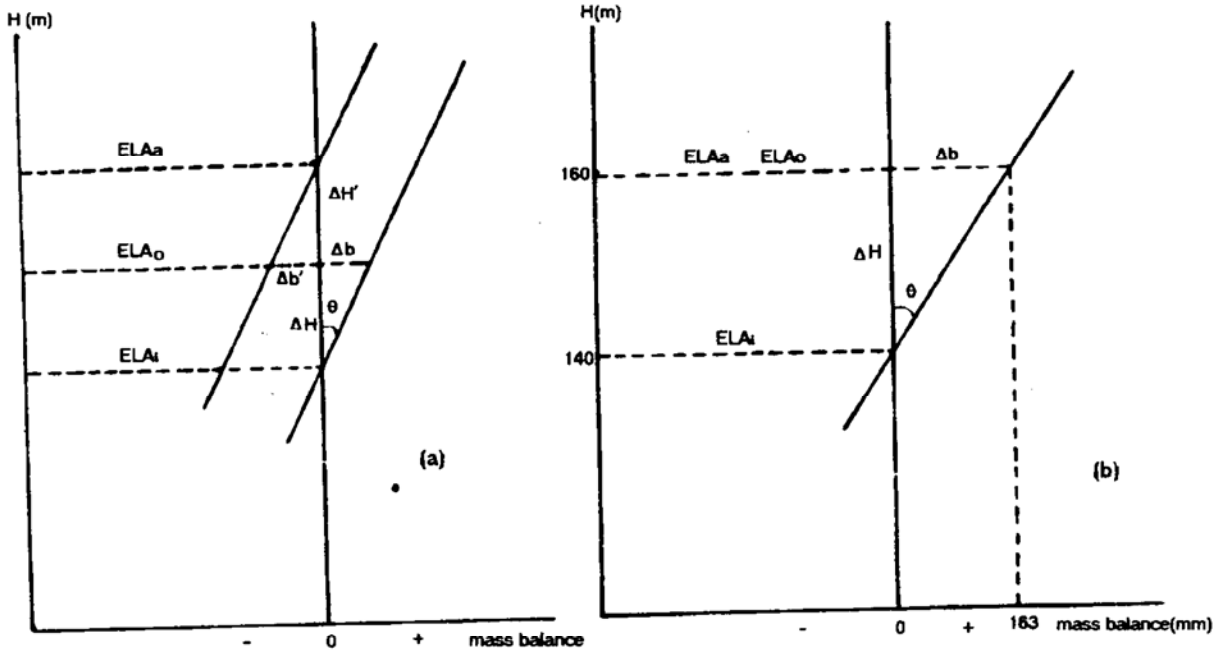

Fig. 2. Relationships of ELAs with net mass balance.

4. 2 Determination of the equilibrium line altitude under the stable equilibrium state

The average mass balance value b_n was 163 mm at section SDS of small dome in 1991/1992, from above, Δb was 163 mm at ELA_0 in the mass balance year of 1991/1992. Furthermore, according to many glacial reseach results, the interannual variations of the mass balance gradient Eg was not large (Aizen, 1985; Chen and Funk, 1990; Meier and Tangborn, 1965). In the fluctuation zone of equilibrium line of small dome, Eg was 8. 4 mm/m, substituting to equation (3), we could get the difference ΔH between ELA_0 and ELA_i was 20 m, i. e. ,ELA_0 was 160 m or 20 m higher than ELA_i. This altitude was equal to the heigt of dynamic equilibrium line (ELA_a) (Fig. 2b), it meaned the small dome of Collins Ice Cap was in a relatively stable state for a long time.

4. 3 Discussion

4. 3. 1 Determination of the equivalent mass balance at ELA_0.

Based on the research of Kotlyakov and Krenke (1982), the relationship between the total ablation A (mm) and summer (3 months) mean temperature T_s at ELA_i (or ELA_0) is:

$$A = 1.33\ (9.66 + T_s)^{2.85} \qquad (9)$$

The tatol ablation calculated by equation (9) was 720 mm at ELA_0 of small dome in

1991/1992, it was higher than the measured value (629 mm), so the coefficient of equation (9) was adapted as follows:

$$A = 1.1\ (9.66 + T_s)^{2.85} \tag{10}$$

The summer mean temperature was 0.0 ℃ at ELA_0 of small dome (Table 1), substituting to equation (10), A was 706 mm. At ELA_0, when summer mean temperature increased or decreased 1.0 ℃, the decrease or increase values of the mass balance were defined as equivalent mass balance b_e. The average b_e at ELA_0 calculated from equation (10) was 211 mm.

4.3.2 Calculation of mass balance variations at EAL_0

Thus, by the use of deviations to the stable equilibrium state (706 mm, 0.0℃) caused by total accumulations and summer mean temperatures, variations of net mass balance could be calculated.

As small dome was a typical ice cap, and its surface was relatively smooth, the effect of snow draft to accumulation could be neglected. So the increase or decrease of precipitation could be taken as the changes of accumulation. Furthermore, Frei Meteorological Center is only about 3 km away from small dome, and elevation difference (150 m) between ELA_0 and Frei Center is very small. Therefore, we can assume the gradient between average precipitation (500 mm) at Frei Center and average accumulation (706 mm) at ELA_0 was stable. Thus, the deviations ΔP_{il} of accumulation at ELA_0 were equal to the anomalies ΔP_i of annaul precipitation at Frei Center; As the same, deviations ΔT_{sil} of summer mean temperatures at ELA_0 were equal to the anomalies ΔT_{si} at Frei Center. Then, by the use of equivalent mass balance b_e, mass balance variations b_{ti} caused by temperature counld be calculated. When ΔT_{sil} were negative, b_{ti} were positive, conversely, when ΔT_{sil} were positive, b_{ti}, negative.

Mass balance variations (b_l) in different mass balance years could be calculated as follows:

$$b_l = b_{pi} + b_{ti} \tag{11}$$

b_{pi}, b_{ti} represented the contributions of precipitations and temperatures to the mass balance separately:

$$b_{pi} = \Delta P_{il} = P_{il} - P_l = \Delta P_i \tag{12}$$

$$b_{ti} = -\Delta T_{sil}\, b_e \tag{13}$$

where, P_{il}, P_l were the precipitations and mean annual precipitation at ELA_0 in each mass balance year.

The interannual changes of mass balance at ELA_0 were calculated by the use of the anomalies of summer mean temperatures and precipitations of Frei Center in each mass balance year, results are presented in Table 4. The accumulative variations are shown in Figure 3. From Fig. 3, we found that mass balances were mainly negative from 1971/1972 to 1983/1984, the maximum of accumulative negative mass balance was up to −909.6 mm, equal to annual mass turnover of small dome, i. e., mass balance level

Table 4. Calculated mass balance variations at (ELA_0) of small dome, Collins Ice Cap.

Mass balance year	P_{il} (mm)	b_{pi} (mm)	$\sum b_{pi}$ (℃)	ΔT_{sil} (mm)	b_{ti} (℃)	$\sum b_{ti}$ (mm)	b_l (mm)	$\sum b_l$ (mm)
1971—72	507.1	−198.9		−0.62	130.8		−68.1	
1972—73	585.5	−120.5	−319.4	−0.29	61.2	192.0	−59.3	−127.4
1973—74	521.2	−184.8	−504.2	0.21	−44.3	147.7	−229.1	−356.5
1974—75	645.5	−60.5	−564.7	−0.12	−25.3	173.0	−35.2	−391.7
1975—76	650.2	−55.8	−620.5	−0.09	19.0	192.0	−36.8	−428.5
1976—77	566.7	−139.3	−759.8	−0.62	130.8	322.8	−8.5	−437.0
1977—78	717.1	11.1	−748.7	−0.09	19.0	341.8	30.1	−406.9
1978—79	611.2	−94.8	−843.5	0.38	−80.2	261.6	−175.0	−581.9
1979—80	798.4	92.4	−751.1	0.14	−29.5	232.1	62.9	−519.0
1980—81	661.8	−44.2	−795.3	−0.19	40.1	272.2	−4.1	−523.1
1981—82	760.3	54.3	−741.0	0.58	−122.4	149.8	−68.1	−591.2
1982—83	553.7	−152.3	−893.3	0.04	−8.4	141.4	−160.7	−751.9
1983—84	556.7	−149.3	−1042.6	0.04	−8.4	133.0	−157.7	−909.6
1984—85	954.6	248.6	−794.0	0.58	−122.4	10.6	126.2	−783.4
1985—86	919.0	213.0	−581.0	0.11	−23.2	−12.6	189.8	−593.6
1986—87	707.4	1.4	−579.6	−0.26	54.8	42.2	56.2	−537.4
1987—88	546.3	−159.7	−739.3	0.14	−29.5	12.7	−189.2	−726.6
1988—89	726.4	20.4	−718.9	−0.06	12.7	25.4	33.1	−693.5
1989—90	970.2	264.2	−454.7	0.81	−170.9	−145.5	93.3	−600.2
1990—91	1133.8	427.8	−26.9	−0.19	40.1	−105.4	467.9	−132.3
1991—92	724.6	18.6	−8.3	−0.56	118.2	12.8	136.8	−4.5

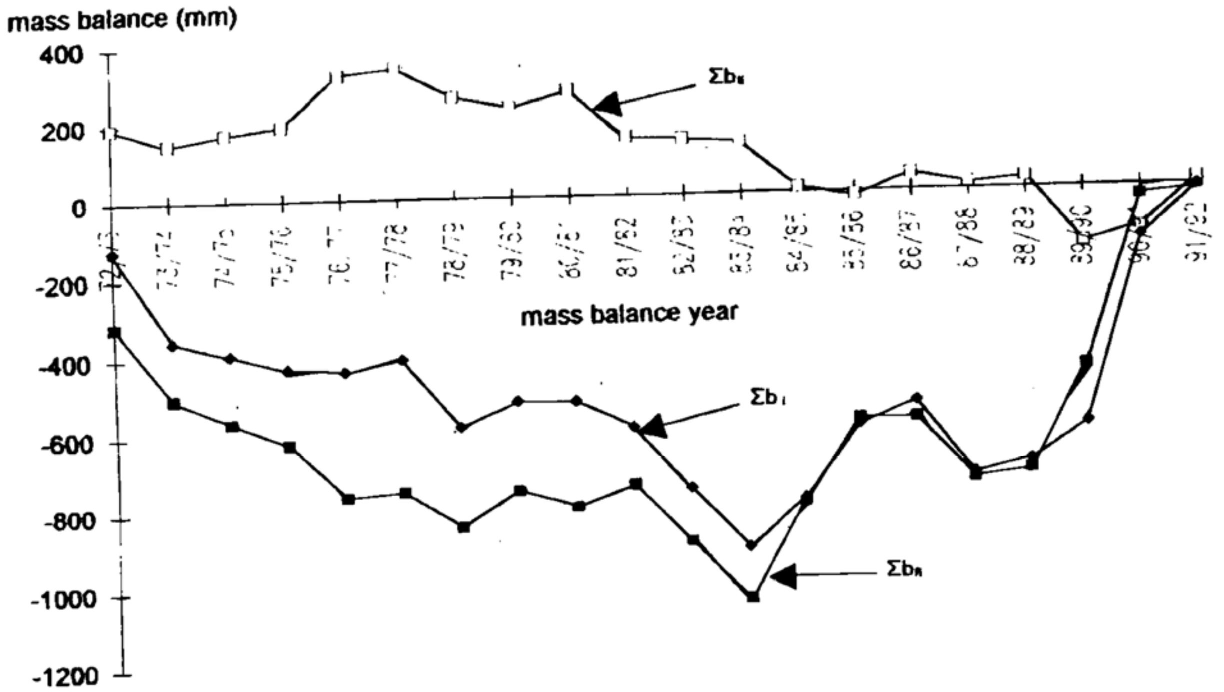

Fig. 3. Accumulative contributions of temperatures and precipitations to mass balance.

(928 mm). After that, mass balance were mainly positive, the trend of mass balance in 21 years was close to zero.

5 Conclusion

1. According to short-term meteorological observations, vertical temperature gradients on the small dome were −0.79℃/100m and −0.66℃/100m in the summer and the winter.

2. Though the mean annual temperature was as high as to −3.5℃ at equilibrium line, average summer temperature was lower(only about 0.0℃), so the ice cap could be developed in this area.

3. In 1991/1992 small dome of Collins Ice Cap was a weak positive balance year with a mass balance difference of 163 mm, the annual ELA was 140m. Mass balance gradient and mass balance level were 8.4 mm/m and 928 mm separately.

4. Mass balance fluctuations on the small dome in 1971—1992 were calculated by a new method. the results showed that glacial mass balance was negative mainly before the middle of 1980's, and after that, the positive dominated as the increased precipitation was beneficial to the glacial development. The small dome had the trend of stable equilibrium state over 21 years.

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