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Glaciological observations in the Tanggula Mts., Tibetan Plateau

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Abstract

Five years' mass balance monitoring and two years' monitoring of climatic conditions were performed and intensive glaciological studies were carried out in summer, 1993 on Xiao Dongkemadi Glacier, Tanggula Mountains. During the intensive observation period, internal accumulation and albedo which largely control mass balance of the glacier were studied. In 1993, major melting occurred within 1 month from late July to mid-August. Large seasonal amplitude of air temperature and strong incoming solar radiation cause considerable internal accumulation ; superimposed ice was formed in the major melting period. Rather strong wind and arid surface environment in the dry season on the plateau carry aeolian materials onto the glacier, form a distinct dirt layer and influence the albedo. Average annual net accumulation from 1990 to 1992 is estimated to be about 1000 mm in the accumulation area on the glacier.

1. Introduction

Glaciers play an important role in hydrological cycle on the Tibetan Plateau, and attention is being paid to the recent variations of glaciers on the Tibetan Plateau during on-going climatic change. CREQ (Cryosphere Research on Qingzang Plateau) Project aimed to investigate the hydrological cycle in which the cryosphere plays a dominant role (Ageta *et al.*, 1994). Glaciological works are important for CREQ in following points ;

1) A considerable amount of solid water is stored in the glaciers.

2) The annual hydrological cycle is greatly affected by glacier ablation (Ohta *et al.*, 1994).

3) The variation of the hydrological cycle is memorized in the glaciers as variations of strata, isotopes and dust.

The Tanggula Mountains are located in the middle part of the Plateau. We have carried out glaciological observations since 1989 on the glaciers in Dongkemadi Valley located in the middle part of the mountain range (Fig. 1). Two glaciers, Da(large) and Xiao(small) Dongkemadi Glaciers, exist in the valley. Our glaciological studies since 1989 have been carried out mainly on the Xiao Dongkemadi Glacier because of its easy accessibility (Ageta *et al.*, 1991). Automatic snow depth gauges and an Aanderaa Automatic Meteorological Station were set at 5600 m around the equilibrium line altitude (ELA) of the glacier in May 1989 and September 1991 respectively. In 1993, a Glacier Camp (GC) was installed on May 21 near the side moraine of the glacier and we started intensive field studies until the middle of September. The purpose of this report is to give an outline and preliminary results of the intensive glaciological study in 1993.

Glaciers in the Tanggula Mts., including the Dongkemadi glaciers, are classified as continental type (Chinese Academy of Sciences, 1986 ; Ding *et al.*, 1992), located in a dry and cold environment ; the ice temperature is low. Besides continuous mass balance observations, our study focused on characteristic processes occurring in continental type glaciers. One of them is internal accumulation caused by strong solar radiation due to the rather low latitude (33 °N)

Fig. 1. Location map around Dongkemadi glaciers. Shaded area are glaciers, and 'X' and 'D' denote Xiao and Da Dongkemadi Glaciers respectively. Contour interval is 100 m.

and large seasonal amplitude of temperature. Cooling in winter is strong enough to lower the ice body temperature well below 0 °C. The negative temperature memorized in the ice body causes percolated water to refreeze in the next summer. We also studied the effect of impurities on albedo, which is expected to be strong, because a semi-desert area exists on the western part of the Plateau. Hence, the objectives of the intensive glaciological works in CREQ 1993 were to :

1) monitor the mass balance and climatological elements continuously around ELA.

2) clarify the amount of internal accumulation forming superimposed ice and climatic condition which controls internal accumulation.

3) monitor the variation of albedo and investigate characteristics of impurities.

4) collect several years' snow and ice samples for measuring variation of stable isotope and dust contents, and estimating annual accumulation.

2. Observation items, sites and methods

Observation items, sites, periods and intervals are summarized in Table 1. Figure 2 shows the topography of the Xiao Dongkemadi Glacier and locations of the observation instruments. This map is based on a survey by using a laser rangefinder and a theodolite (Wild T1600) on June 11 and 12, 1993.

Automatic snow depth gauges, which record the glacier surface level using photo diode sensors (Kadec Snow) or glass-fibre sensors (Aburakawa snow depth recorder) were set at 3 altitudes (5700, 5600 and 5500 m a.s.l.) corresponding to the accumulation area, ELA and ablation area respectively. The automatic measurements were replaced by manual recording in cases of instrument trouble. Pits down to the interface between snow and superimposed ice were dug at 3 altitudes (5600 m, 5650 m and 5700 m) at about 10-day intervals. Stratigraphy, density, grain size, temperature and liquid water content were observed in the pits. Liquid water content was measured by Denoth dielectric meter (Denoth, 1990).

An Aanderaa automatic meteorological station (AMS) has been working since September, 1991 around the ELA of the glacier (5600 m). Air tempera-

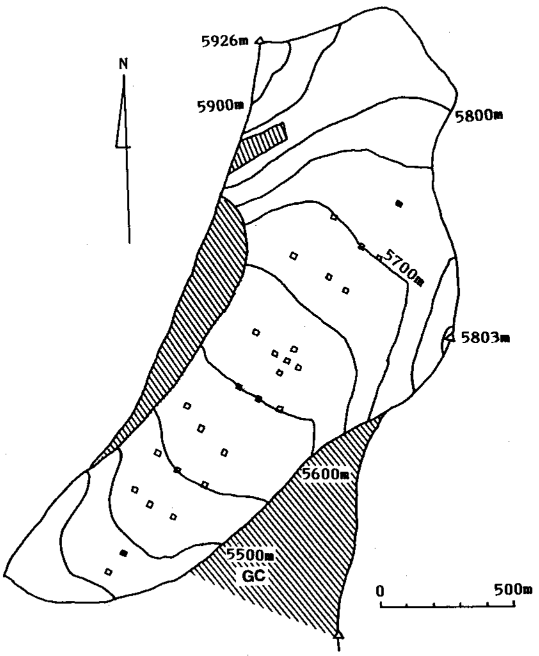

Fig. 2. Location map of stakes (open square) and automatic snow depth gauges (solid square) on Xiao Dongkemadi Glacier. GC denotes Glacier Camp.

Table 1. Observation elements on Xiao Dongkemadi Glacier
(IOP: intensive observation period from May to September, 1993).

Items	Sites (altitudes)	Period	Interval
Surface level	St+2 (5500m)	IOP	
	St 3 (5600m)	1989, May-	1 hour
	St 9 (5700m)	IOP	
Meteorological elements	5600m	1991, Sep.-	1 hour
Air temperature			10 min. in IOP
Relative humidity			
Wind velocity			
Wind direction			
Global radiation (up and down)			
All radiation (up and down)			
Albedo	5600m	1991, Oct. -	(as above)
	5500m, 5700m	IOP	30 min.
Spectral albedo	several sites	IOP	occasionally
Ice temperature	5680m, 5600m, 5500m	1992, Oct. -	about 10 days
Snow pit studies	5700m, 5650m, 5600m	IOP	about 10 days
stratigraphy			
density			
grain size			
liquid water content			
sampling			
Percolated water amount	5700m	IOP	about 10 days
5m coring	5700m, 5650m		once
Precipitation	GC (5500m)	IOP	twice
amount			(with intermission)
sampling			

ture, relative humidity, wind velocity, wind direction, shortwave radiation (upward and downward) and all-wave radiation (upward and downward) have been monitored at 1-hour intervals since 1991 and 10-minute intervals during the intensive observation period. Precipitation was recorded twice a day at Glacier Camp (GC : 5500 m) by measuring the amount of water in a bucket (Ueno *et al.*, 1994) and samples for stable isotope study were taken simultaneously.

Ice temperature was monitored at 3 altitudes (5680 m, 5600 m and 5500 m) using thermistors at 2, 4, 8 and 16 m in depth. They were installed in October, 1992. Automatic recording started from the time of installation, but the automatic recorder did not work well after January 1993. Manual measurements of thermistor resistance were carried out about every 10 days during the intensive observation period.

Albedo on the glacier was monitored at two altitudes (5700 m and 5500 m) in addition to AMS (5600 m) using coupled pyranometers. From the end of May to the middle of September, albedos at 3 altitudes were measured simultaneously, while there were several interruptions of tens of days. Spectral albedos of snow and ice were measured occasionally at several altitudes. A 'Personal Spectrometer II' (Analytical Spectral Devices Inc.) was used for measuring spectral albedo from 380 nm to 1080 nm at 1.4 nm intervals in wave-length. Measurements were carried out by comparing reflected light intensity from glacier surfaces with that from a certified reflectance standard which has nearly unity albedo across these wavelengths.

Samples of snow and ice were taken at several altitudes to analyze the stable oxygen isotope content ($\delta^{18}O$) and dust content. Samples were divided into pieces of 10 cm each in depth and melted at GC. Stable isotope content and dust content were measured by a mass spectrometer (MAT250) and a Coulter counter (Coulter Multisizer II), respectively. Samples of dirt layers and surface dirt at several altitudes were used for studying impurities including dust and biomass.

3. Results

a) Mass balance and internal accumulation

Figure 3 shows the variation of surface level at 5600 m a.s.l. (around ELA) on Xiao Dongkemadi

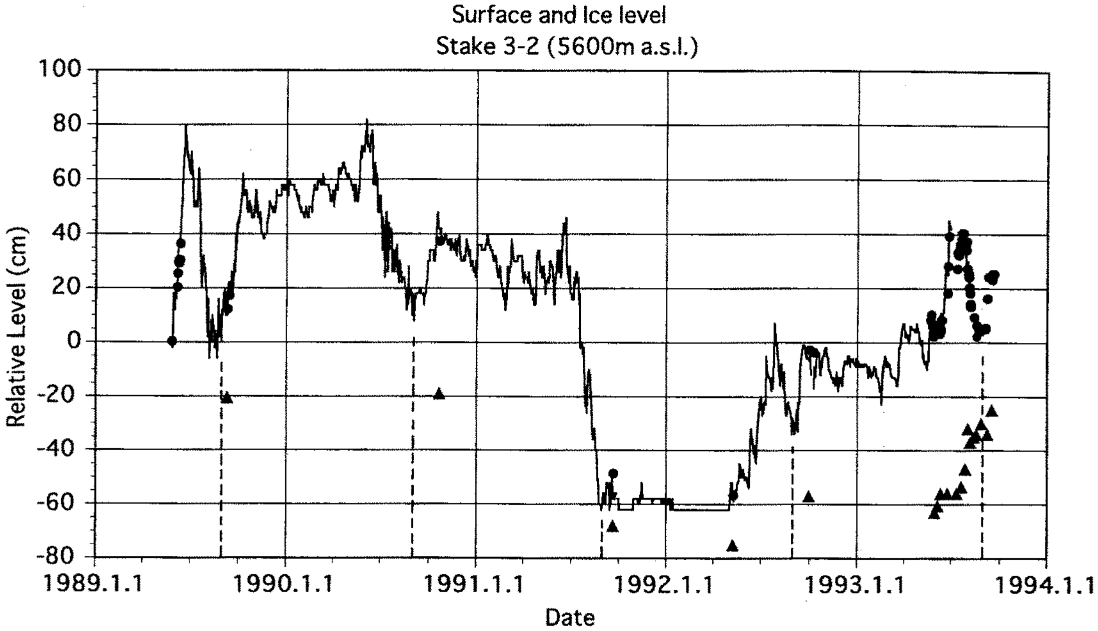

Fig. 3. Variation of surface level at 5600 m a.s.l. on Xiao Dongkemadi Glacier from May 1989 to August 1993. The levels of the interface of snow and superimposed ice are shown with solid triangles. (solid circle : surface level measured by manual observation, dashed line : the end of August)

Glacier during the 5 years since May, 1989. The variation of surface level in winter is rather small compared with that in summer, except for a few occasional increases. Large net accumulation usually occurred in June and in September, large ablation took place in July and August. From the annual variation of the surface level in Fig. 3, glacier mass is considered to have reached a minimum at the end of August in each annual cycle. Consequently, the measurement year of glacier mass balance in this area is defined from the beginning of September to the end of August. During these 4 measurement years, the mass balance at 5600 m was positive in 1989/90, 1991/92 and 1992/93, but largely negative in 1990/91.

Figure 4 shows the variation of surface level during the 1992/93 measurement year and the interface level between snow and superimposed ice during the intensive observation period in 1993. Automatic recording was interrupted due to several troubles including damage caused by electric shock by thunder frequently occurring in summer. The snow surface level clearly started to increase from May until the end of June corresponding to the beginning of the monsoon season. Especially, in the latter part of June, a large amount of snowfall occurred and surface level increased. Apparent decrease of surface level took place from late July and continued until mid-August, lasted for one month only. The snow level increased 34 cm from September 1992 to September 1993. Both specific mass balance at 5600 m a.s.l. and total mass balance of the glacier were positive in the 1992/93 measurement year (Pu and Yao, 1994).

The variation of interface level between snow and superimposed ice was monitored in pits dug about every 10 days during the summer, 1993 and is expressed by solid triangles and horizontal bars in Figs. 3 and 4, respectively. In winter, there is no apparent change in the level. Although a slight increase of ice level can be found from the end of May, it remains stationary until late July. It shows remarkable increase within 1 month from late July to August, corresponding to the rapid decrease of surface level.

Figures 5 and 6 show stratigraphy, density and snow temperature in firn observed at 5700 m and 5600 m at the beginning and end of the intensive observation period. The snow-ice interface exists at rather shallow depth (at 132 cm and 177 cm from the surface in May and September, respectively) even in the upper part of the glacier (5700 m). Firn temperature was below 0 °C at both altitudes in May and became zero

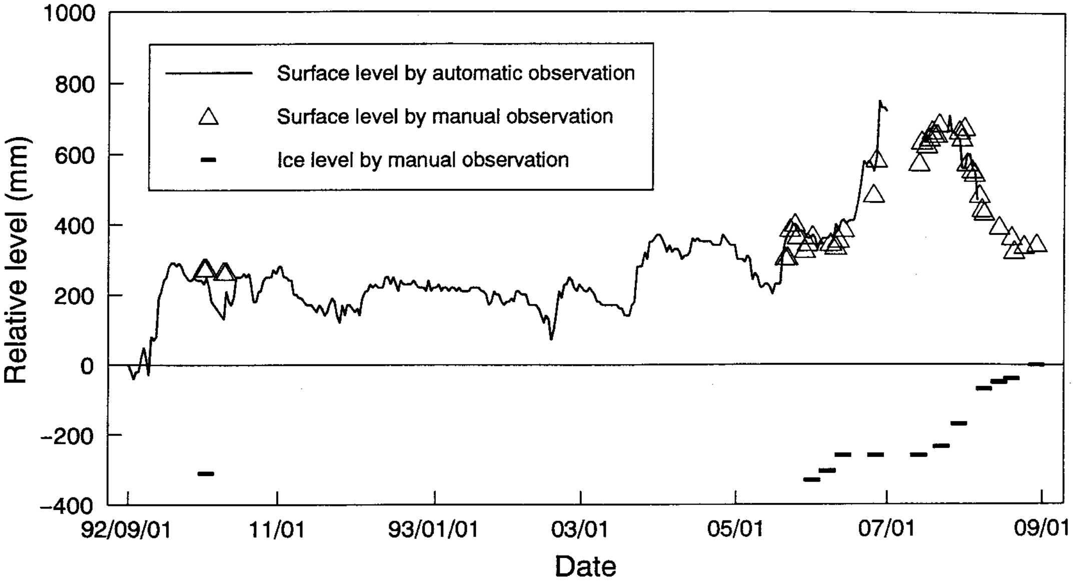

Fig. 4. Same as Fig. 3 during the period from September 1992 to August 1993.

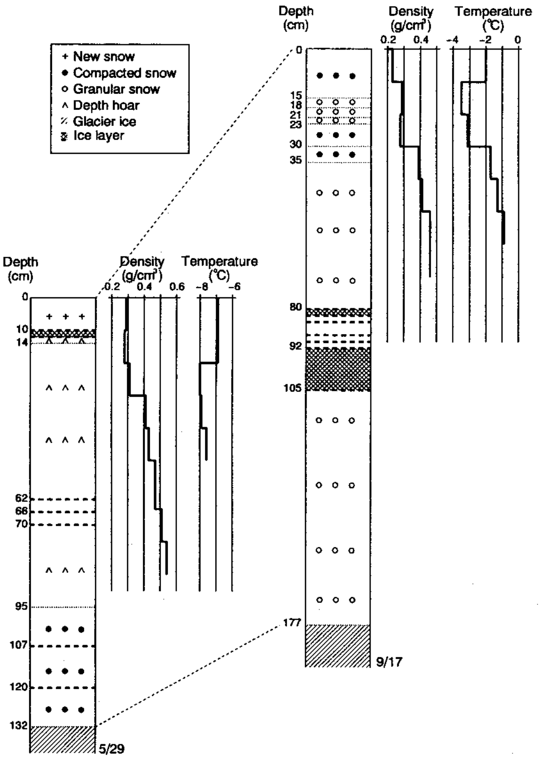

Fig. 5. Strata, profiles of density and temperature at 5700 m a.s.l. on Xiao Dongkemadi Glacier in May and September, 1993.

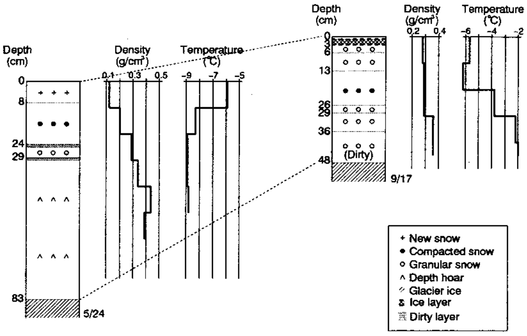

Fig. 6. Same as Fig. 5 at 5600 m a.s.l.

in late June, and melting continued until mid-August independent of altitude. Before melting occurs, a distinct depth hoar layer which has large grain size (3 mm—4 mm in diameter) developed for several tens of centimeters in thickness. Once melting started, depth hoar metamorphosed into granular snow. Snow density increased with depth from about 0.2 gcm^{-3} in the shallow part to about 0.5 gcm^{-3} in the deeper part. Volumetric liquid water content in the firn ranged from 3 to 5% during the melting period.

Figure 7 shows the seasonal variation of percolating water flux at two altitudes. Percolating water was measured about every week at 2 altitudes (5700 m and 5600 m) for estimating the water supply to make

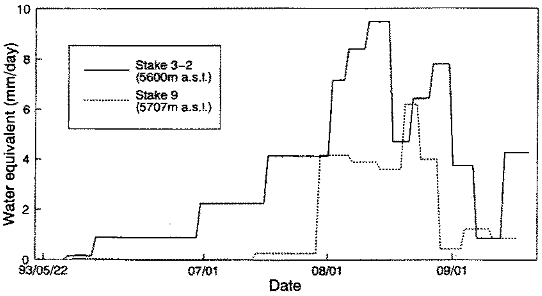

Fig. 7. Variations of amount of percolated water observed at 5600 m and 5700 m, observed at Xiao Dongkemadi Glacier from May to September, 1993.

superimposed ice. The amount of melt water was measured by weighing bottles set from 10 cm to 20 cm below the snow surface in a manner similar to that used by Ageta *et al.* (1989). The amount increased drastically in late July corresponding to the beginning of decrease of surface level and increase of snow-ice interface as shown in Fig. 4. The total amount of percolating water measured at 5700 m (149 mm) is less than half of that at 5600 m (408 mm).

b) Ice temperature

Figure 8 shows the englacial temperature profile from October, 1992 to September, 1993 recorded at 5600 m (around ELA). This glacier is classified as sub-polar type, meaning that the annual mean temperature of the ice body is below 0 °C. The ice temperature profile in January shows remarkable cooling near the surface. In May, while surface temperature increases, the deeper part of the ice body from 2 m to 10 m is cooled by heat conduction to the chilled layer. During the summer until September, ice temperature gradually increases, probably due to latent heat released at the snow-ice interface by refreezing of percolated water.

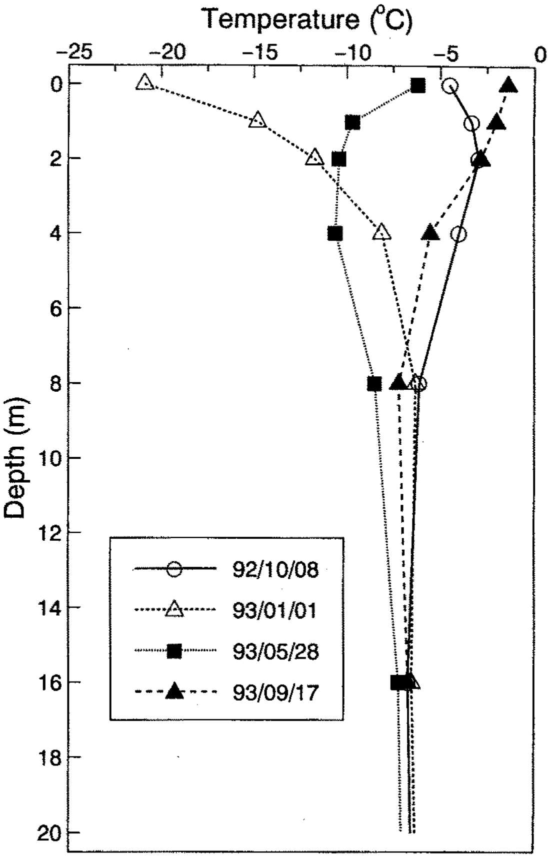

Fig. 8. Seasonal variation of ice temperature of Xiao Dongkemadi Glacier at 5600m a.s.l. from October 1992 to September 1993.

c) Climatological conditions around ELA

Figure 9 shows 2 years' variation of daily mean temperature, relative humidity, wind speed and global radiation recorded at 5600 m (around ELA) from September 1991 to September 1993. The temperature has large seasonal amplitude exceeding 20 °C and rises above 0 °C during one month around August. The large seasonal amplitude of air temperature forms a sub-polar type glacier. Average wind speed during the 2 years is about 4 $\mathrm{ms^{-1}}$; occasional high wind speed exceeding 10 $\mathrm{ms^{-1}}$ can be seen from winter to spring. Relative humidity ranges from 60 % to 90 %, showing slight increase in the monsoon season. Variation of global radiation is mainly affected by the solar zenith angle and clouds. Low cloud amount and low solar zenith angle in April, May and June cause the strongest downward radiation on the glacier. Averaged energy flux from June to August is 280$\mathrm{Wm^{-2}}$ and 1.2 times that measured at Glacier No.1 in the Tiaw-n Shan (Ohmura *et al.*, 1990) and about 1.5 times of that observed on glaciers in Nepal Himalayas (Ohata *et al.*, 1978 ; Kohshima *et al.*, 1993). Shortwave radiation is an important factor for controlling mass balances of these glaciers in the Asian highlands. The large amount of melting in the accumulation area on the Xiao Dongkemadi Glacier (Fig. 7) and the resulted large amount of internal accumulation are largely controlled by the strong shortwave radiation.

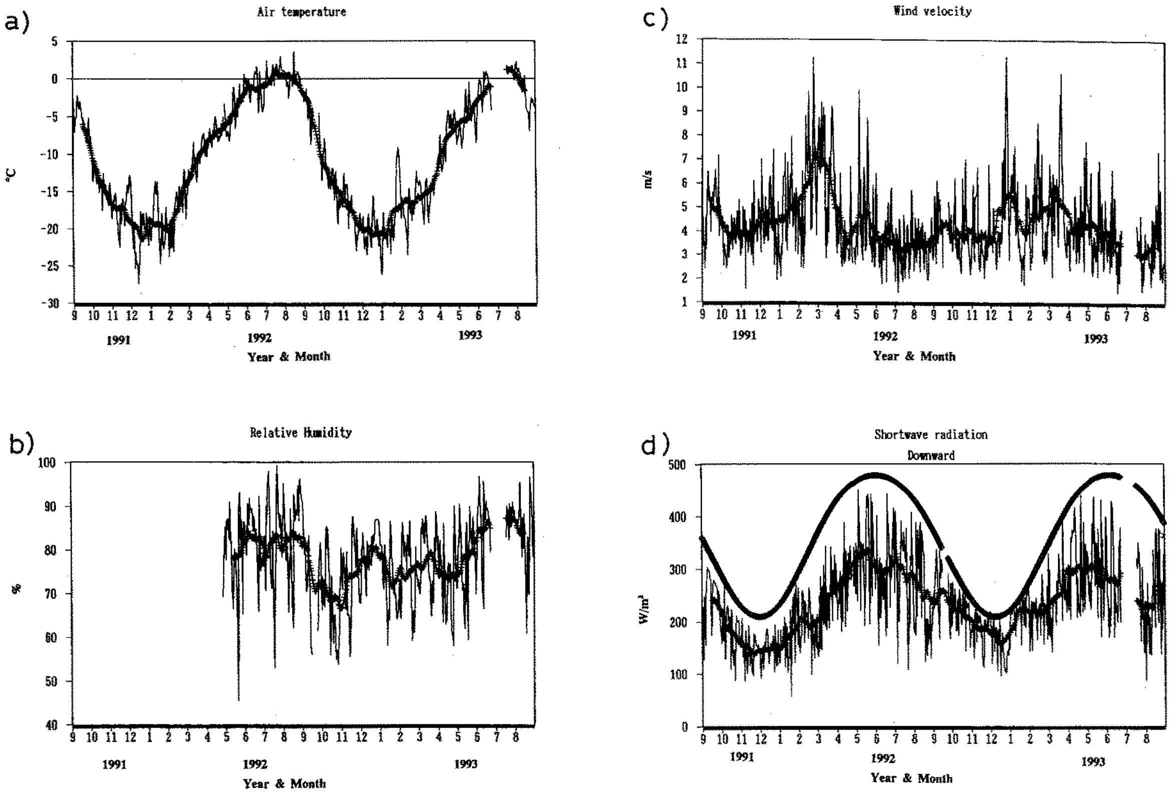

Fig. 9. Climatic condition at 5600m on Xiao Dongkemadi Glacier from September 1991 to September 1993. Eleven-day running means of each element are expressed by thick lines. a) Air temperature, b) Relative humidity, c) Wind speed, d) Downward shortwave radiation (radiation at the top of the atmosphere is also shown.).

d) Albedo

Figure 10 shows the fluctuation of 5-day averaged albedo at three altitudes. Albedo in the ablation area (5500 m) was less than 50 % from the end of July to the end of August, corresponding to the ablation season when bare ice was exposed. In the melting period, a drop of about 10 % can be seen also at 5600 m ; short-term fluctuation with about 10-day interval can be seen before July. Similar short term fluctuation between 70 and 80 % in albedo is noticed even at 5700 m before July. Increase of albedo corresponds to several significant snowfall events ; this fluctuation is attributed to masking of the aged snow surface by fresh snow.

A longer data record, since September 1991, is available at 5600 m (around ELA) as shown in Fig. 11. Remarkable albedo reduction occured in March and April in both 1992 and 1993. This is probably due to dust deposition on the surface, concentration of the dust and surface melting (exposure of ice layer) in spring.

There is a remarkable difference between spectra of new snow and aged snow as shown in Fig. 12. The data were taken on a sunny day when fresh snow fell the previous night and melted away, and aged snow appeared during the daytime. Aged snow shows lower albedo than new snow in two spectral ranges, shorter than 600 nm and longer than 900 nm in wavelength. The decrease at short and long wavelengths shows the effect of dust on snow and the effect of increased grain size (Wallen, 1982). The albedo spectrum on the ice also shows the decrease of albedo at shorter than 600 nm wavelength and probably shows the effect of dust.

e) Stratigraphy, and oxygen isotope and dust contents

Figure 13 shows visual stratigraphy and corresponding stable oxygen isotope contents of 5 m sam-

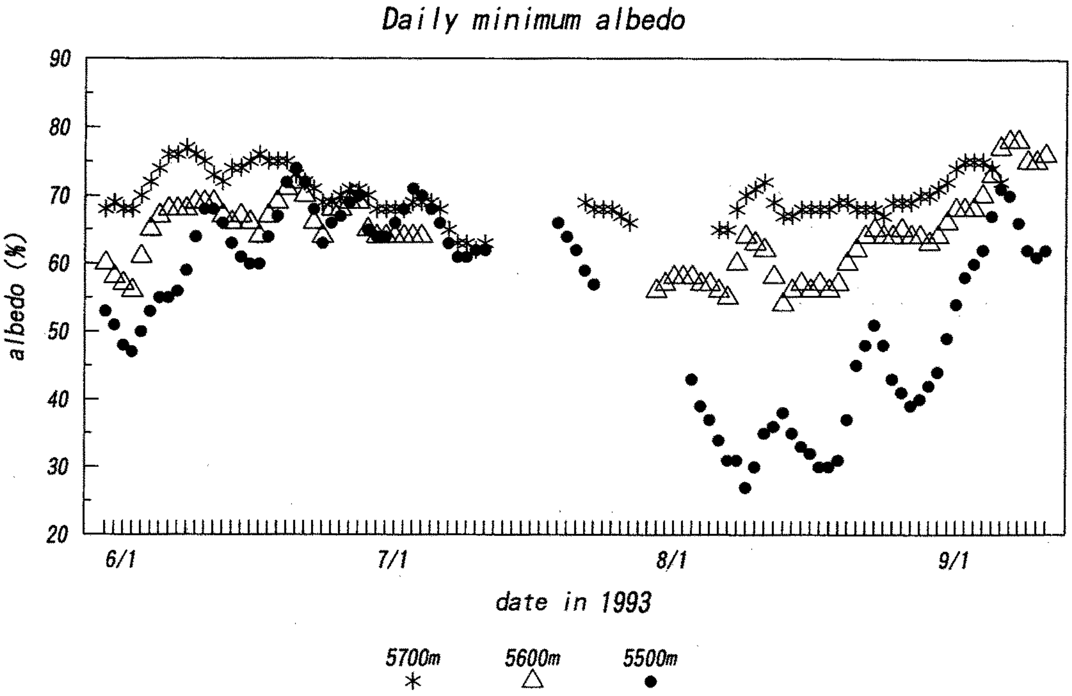

Fig. 10. Variations of albedo at 3 altitudes on Xiao Dongkemadi Glacier during the intensive observation period, 1993. Five-day running means of daily minimum albedo are shown.

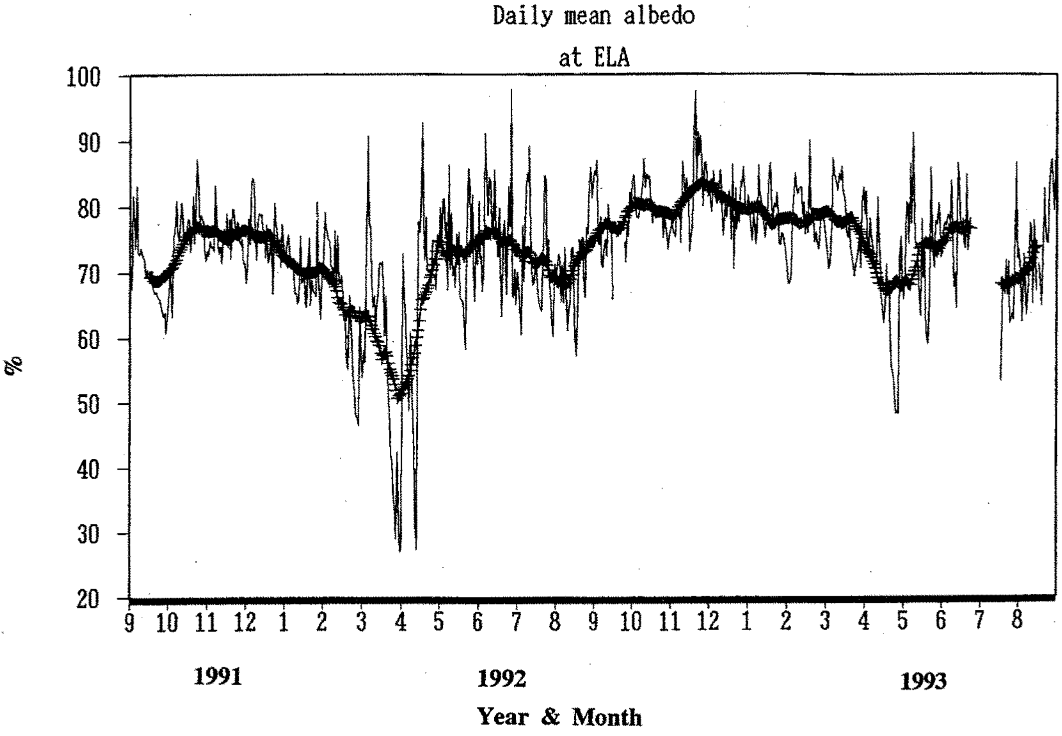

Fig. 11. Variation of albedo measured at 5600 m on Xiao Dongkemadi Glacier from September 1991 to September 1993.

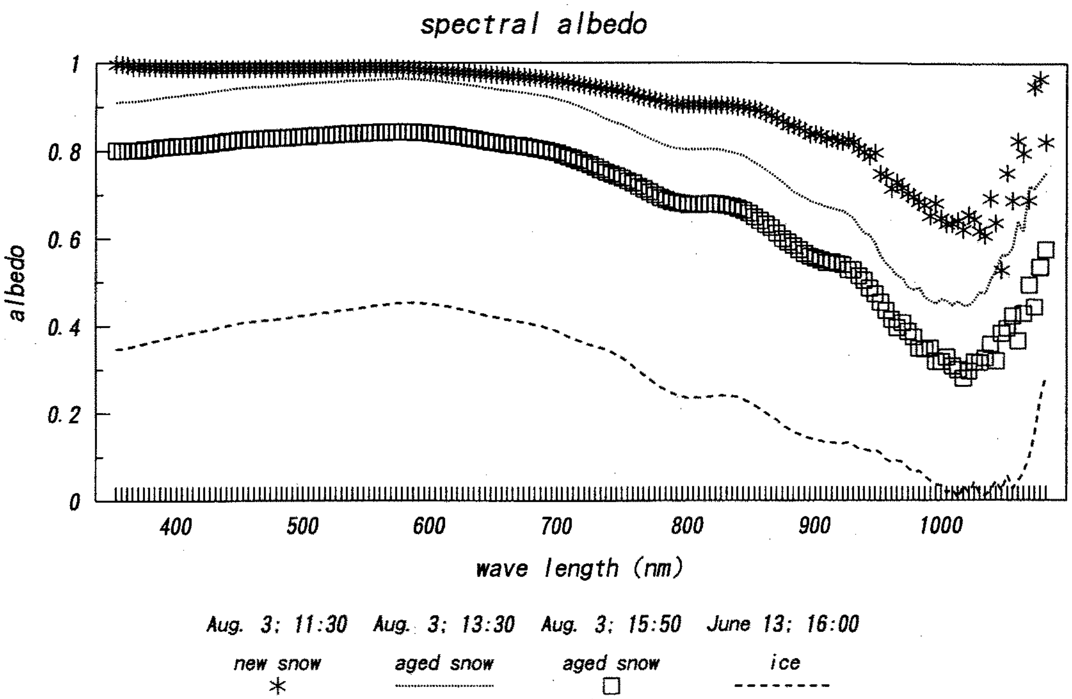

Fig. 12. Characteristic spectral albedo of fresh snow, aged snow and ice on Xiao Dongkemadi Glacier measured at 5600 m on August 3 (snow) and 5500 m on June 12 (ice), 1993.

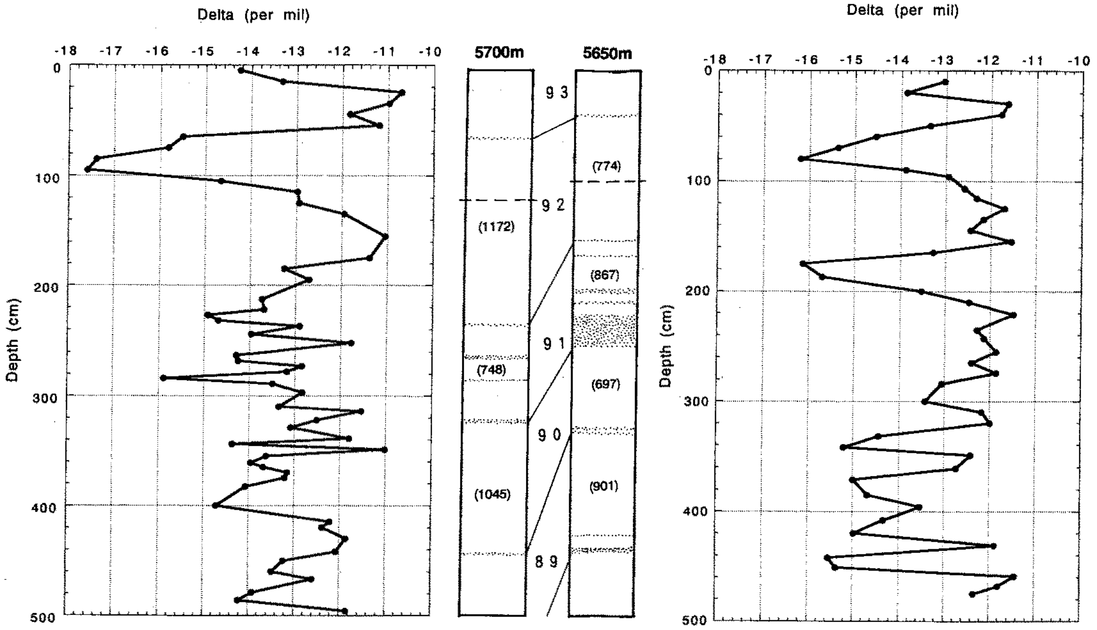

Fig. 13. Strata and stable oxygen isotope content in 5 m samples taken at 5700 m (left) and 5650 m (right) on Xiao Dongkemadi Glacier on August 6 and July 20 in 1993, respectively. Dots and dashed lines in strata denote distinct dirt layers and the interface between snow and ice, respectively. Annual net accumulation (mm water) in each year and at each altitude are shown in parentheses.

ples taken at 5650 m and 5700 m. A snow-superimposed ice interface exists at about 1 m depth, with continuous glacier ice below. Distinct dirt layers are a good indicator of annual accumulation, because a dirt layer is generally formed in the dry season. According to visual interpretation of distinct dirt layers, annual net accumulations in each balance year were obtained. Mean annual net accumulation for 3 years (1989/90–1991/92) is estimated to have been 990mm and 670 mm water at 5700 m and 5650 m, respectively. Annual net accumulation in 1990/91 is estimated to have been less than that in a normal year and corresponds to the surface level lowering measured at 5600 m as shown in Fig. 3.

Profiles of stable oxygen isotope content in the 5m samples taken at 5650 m and 5700 m are also shown. The variation has a clear seasonal signal in the shallow part (1992 and 1993), while there is considerable percolation of water, as shown in Fig. 7. Minimum stable isotope concentration tends to be found in the deeper part of distinct dirt layers. Profiles older than 1991 seem to be highly disturbed, probably due to large infiltration in 1991, because the mass balance in 1990/91 was negative as shown in Fig. 3. Numbers and sizes of insoluble particles in the samples were counted by Coulter counter. The total dust contents in the 5 m samples are less than 1ppmw and consist of mainly small particles less than 4 μm in diameter. More than 10 times the concentration, and particles larger than 4 μm in diameter, are likely to be found in the visually identifiable dirt layers.

4. Summary and future research

Five years' surface level and two years' climatological elements around ELA have been monitored on Xiao Dongkemadi Glacier, Tanggula Mts., Tibetan Plateau. During the intensive observation period of CREQ from May to September, 1993, we carried out process studies of internal accumulation and albedo, which are considered to be important for understanding the glacier mass balance. 5 m samples of snow and ice were taken in order to estimate annual net accumulation during the five years and the seasonal cycles of stable oxygen isotope content and dust content.

The principal results are the following :

1) In the measurement year 1992–93, that was a positive mass balance year on the glacier (Pu and Yao, 1994), major melting started from late July, 1993, and lasted for one month. During the 4 years from 1989, large negative annual balance was observed in 1990/91.

2) Measurements of the interface between snow and superimposed ice, ice temperature and percolating water flux were carried out to study internal accumulation. The result shows that internal accumulation occurs in the melting period from the middle of July and the amount is considerable for assessing glacier mass balance and runoff from the glacier.

3) Incoming short wave global radiation on the glacier is fairy large, and albedo on the glacier is apparently affected by impurities (dust). The heat balance on the glacier surface is largely determined by the radiation budget.

4) Annual net accumulation on the upper part of the glacier is estimated to be slightly less than 1000 mm from the results of 5 m coring. Dust content preserves the characteristic seasonal cycle, while stable isotope content is partly affected by percolated water.

Acknowledgments

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