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Glaciological Studies on Qingzang Plateau, 1989
Part 3. Meteorology and Hydrology

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Abstract

Meteorological and hydrological studies were done on Qingzang Plateau to investigate existing conditions for glaciological phenomena such as glaciers, and also to investigate the role of other form of snow and ice, that is snow cover and permafrost in the water cycle and energy budget in this region. Most work was done in the Tanggula Mountains in the central region of the Plateau from May to June, 1989. Two manned stations were set on ground surface (5170 m a.s.l.) and on glacier (5570 m a.s.l.) and two other automatic observation stations were also set. Areal measurements were made by moving observations, and aerological observations were made by pilot balloons.

This report presents the observation systems and preliminary results of this study. Characteristic features were occurrence of abundant snowfall, partly due to large scale disturbance and partly due to strong local convection (precipitation from cumulonimbus). The $\delta^{18}O$ value of precipitation shows a possibility of precipitation from local origin water vapor. Formation of snow cover resulted in cooling of atmosphere and retardation of deepening of the permafrost active layer. Abundant evaporation was observed from the snow cover and glacier surface. An automatic meteorological observation system is maintained in this region to collect longterm data.

1. Introduction

Meteorological and hydrological observations were done in the central region of Qinzang Plateau to investigate the basic surface energy and hydrological processes occurring in the surface layers in the pre-monsoon season. This was the second phase of the study on the cryosphere on Tibetan Plateau, following the work in the West Kunlun Mountains in the summer of 1987 (Zheng *et al.*, 1988; Ohata *et al.*, 1989; Takahashi *et al.*, 1989). The reason for the selection of this period was to investigate the characteristics during the transition from the dry and cold season to the warm and wet season.

The observations in the Tanggula Mountains in 1989 consisted of following six main observations.

(1) Surface thermal and moisture condition, and heat and water exchange at the ground surface.

(2) Characteristics of permafrost, and conditions of soil moisture and ground water.

(3) Heat and water exchange on the glacier, especially evaporation processes.

(4) The areal variation in meteorological conditions on the scale of a few tens of km.

(5) Characteristics of the atmospheric circulation.

(6) Acquisition of long term metoeorological and ground data using an automatic observation system.

The observation sites are shown in Figs. 1 and 2. The main observation site was Base Camp (BC; 5170 m a.s.l., 33°02'N, 92°02'E) along the Dongkemadi River.

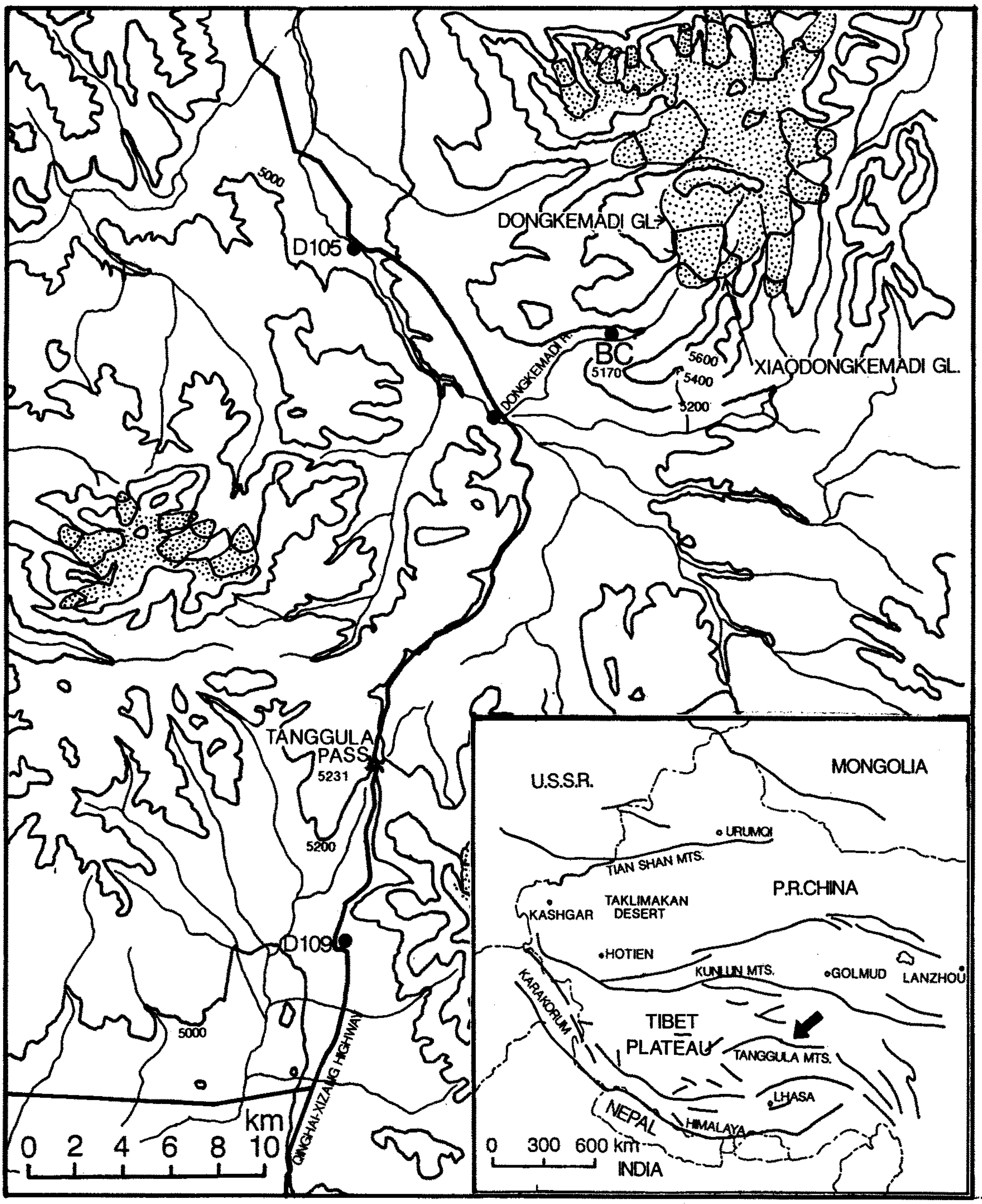

Fig. 1. Map of observation area.

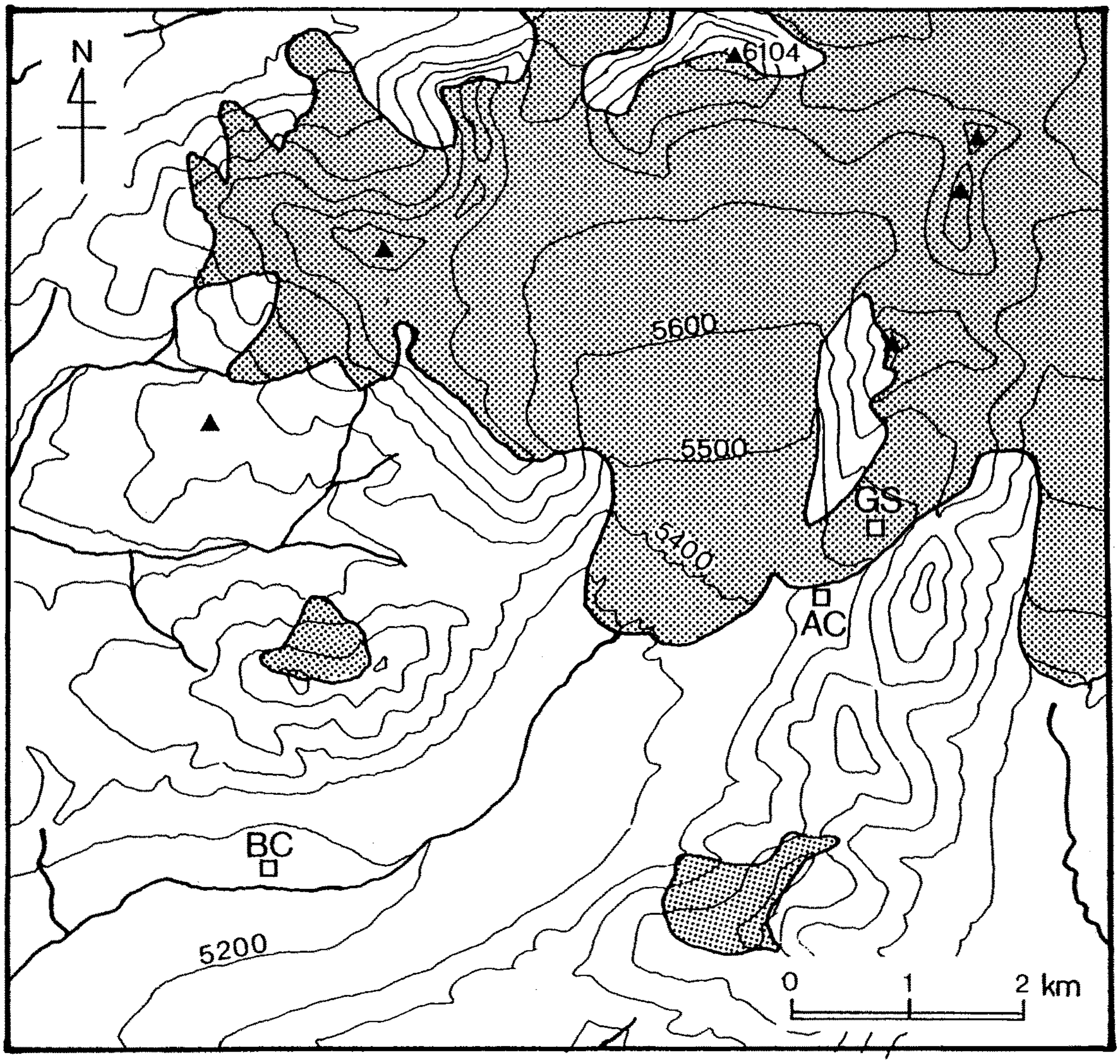

Fig. 2. Positions of stations near the glacier. The glacier is indicated with hatching.

The ground surface condition of this valley consisted of two typical types. One was rather flat surface with short grass, and the other was rather rough and generally wet surface where earth hummocks several tens of cm high developed. The surface water content of the former surface was generally lower than that of the latter surface. BC was located in a area where the former surface predominated.

Other temporary observation sites were Glacier Site (GS) for glacier study, and D105 and D109 where automatic observation systems were set up. GS (5570 m a.s.l.) was set up on the ablation area of the eastern branch of Dongkemati Glacier (Xiaodongkemadi Glacier), and another Advanced Camp (AC; 5440 m a.s.l.) for accomodation on the side moraine of this glacier. GS is situated about 6 km northeast in distance and 400 m higher than BC. Furthermore, periodic moving observation were made along the highway from D105 to D109; observed items were area of snow cover, air temperature and ground texture.

The surface conditions and types of observation done at each site are listed in Table 1. The whole period of observation was from May 12 to June 12, 1989, shortened from the original schedule due to the political situation in China.

The present report will show the main observational results obtained. Analytical and synthetical works will be published later. The time used in the

Table 1 Altitude, surface conditions and observed items at each site

Site	Altitude	Surface condition	Observation period and frequency	Observation item
BC	5170 m	Bare ground with sparse grass slight undulations	May 12–June 12	Surface meteorological elements Radiation balance Ground temperature and water content Piball obs.
GS	5550 m	Snow surface ablation area of Donkemadi Gl.	May 23–June 12	Surface meteorological elements Snow stakes and evaporation
D105	4990 m	Bare ground with sparse grass flat	May 20–	Automatic meteorological obs.
D109	5060 m	In a small settlement at a bottom of a hill	May 20–June 13.	Automatic meteorological obs.
D105-D109	4990–5206 m	Mainly bare ground	few times during May 27 – June 13.	Moving obs. Air temperature Ground moisture and Ground temperature Snow cover

present report is Beijing Standard Time (BST; GMT+8 hours), and local time of the observation area is approximately 1.8 hours behind BST, the local noon being approximately 13:50 BST. The name of the author of each section is written in parentheses at the top of each section.

2. Surface meteorological observations at BC. (Ohata, T.)

Meteorological elements observed and instruments used at BC are shown in Table 2. The daily mean and total values of observed elements are listed in Appendix 1. Main observations were made by an automatic observation system. Other elements such as cloud amount were done by eye observation, and some were done manually.

The variations in mean daily value of the main meteorological elements are shown in Fig. 3. The surface groud layers were quite dry when we arrived at that site on May 11. The precipitation data at the meteorological station located 150 km NNE (Tuotuo He) showed that there was no precipitation before the observation period for more than two weeks.

Air pressure varied of 9 mb during this period, lowest on May 14 and June 6, but the lowest pressure did not correspond to the high precipitation period. Wind speed was generally high except from the end of May to the beginning of June, when there was snow cover.

2.1 Air temperature and humidity

Period mean air temperature was −1.2 ℃; daily mean air temperature varied between −8.4 and 3.7 ℃. Mean daily maximum was 3.6 ℃ and it was higher than 0 ℃ except for four days; mean daily minimum was −6.0 ℃ and it was lower than 0 ℃ for all days. The mean daily temperature range was 9.6 ℃. Large temperature range corresponded to low humidity and high solar radiation; low temperature range corresponded to high humidity and low solar radiation. Period mean relative humidity was 73 %.

2.2 Wind speed and wind direction

The period mean wind speed was 3.2 m/s. Wind speed was low when snow cover existed at the end of May. Fig. 4 shows mean hourly wind speed. Wind speed varied from 2 to 5 m/s during the day. It was weak during the morning hours and was strongest around 17:00.

Frequency of three-hour average wind direction is shown in Fig. 5. The most frequent wind direction were E to SE and W to NW, which is roughly the direction of the valley, but the direction does not show systematic change. The most interesting characteristics of wind direction is the high frequency of NW wind in night hours (3:00-5:00) and high frequency of E wind in the morning hours (09:00-11:00).

2.3 Precipitation

Most precipitation was snowflakes and graupel; on a few occasions hail was observed precipitating from cumulonimbus (Cb). No rainfall was observed, but on some warm days falling snow was partly melting. Due to such conditions and relatively strong wind, 3 to 12 hourly precipitation data observed by reserving rain gauge were calibrated according to the following correction coefficient obtained by Lapin (1989) for snowfall.

$$k_x = 1.05 + 0.0412\ U + 0.0307\ U^2$$

The corrected value coincided with the snow cover water equivalent measurement made for night-time snowfall, which showed higher values in comparison to the uncalibrated precipitation data. Due to this correction, total precipitation became 106.6 mm (Uncalibrated value 74.3 mm), and total precipitation

Table 2 Elements observed,instruments used and frequency of observations at Dongkemadi BC

Elements	Sensors	Accuracy	Type and Obs. Manufacturer	Frequency
Air temperature	Platinum Resistor	0.1℃	Aanderaa Co. (No.3145)	Every 10 min Instantaneous value
Wind speed	3-cup type	0.2% or 20cm/s Whichever greater	same (No.2740)	10min.mean
Wind direction	Potentiometer type	5°	same (No.3150)	Every 10 min. Instantaneous value
Relative humidity	Hygroscopic hair	3%	same (No.2820)	same
Air pressure	Silicon chip	0.8 mb	same (No.2810)	same
Radiations				
Global solar rad.	Pyranometer Temperature difference type (0.3−2.5μm)	2mW/cm²	same (No.2770)	same
	Temperature difference type (0.3−3.0μm)	1.5%	Eko Co. (MS-800)	same
	Temperature difference type (0.72−3.0μm)	1.5%	same	same
Reflected solar rad.	Temperature Difference type (0.3−3.0μm)	1.5%	same	same
	Temperature Difference type (0.72∼3.0μm)	1.5%	same	same
Scattered global solar rad.	Temperature Difference type (0.3−3.0μm)	1.5%	same	same
Net radiation	Net radiometer Temperature Difference type (0.3∼3.0μm)		Eko Co. CN-11	same
Ground temperature (0,-10,-20 cm)	Platinum Resistor	0.1℃	Aanderaa Co.	same
(-30,-50,-60,-70cm)	Mercury Thermometer	0.5℃		every 3hours reading in the daytime
Precipitation Amount	Reserving rain Gauge(∅=20cm)			every 3 hours measurement
Evaporation	Lysimeter			same
Cloud amount and type	Eye observation			same
Surface condition	Eye observation			same
Snow	Measure			same

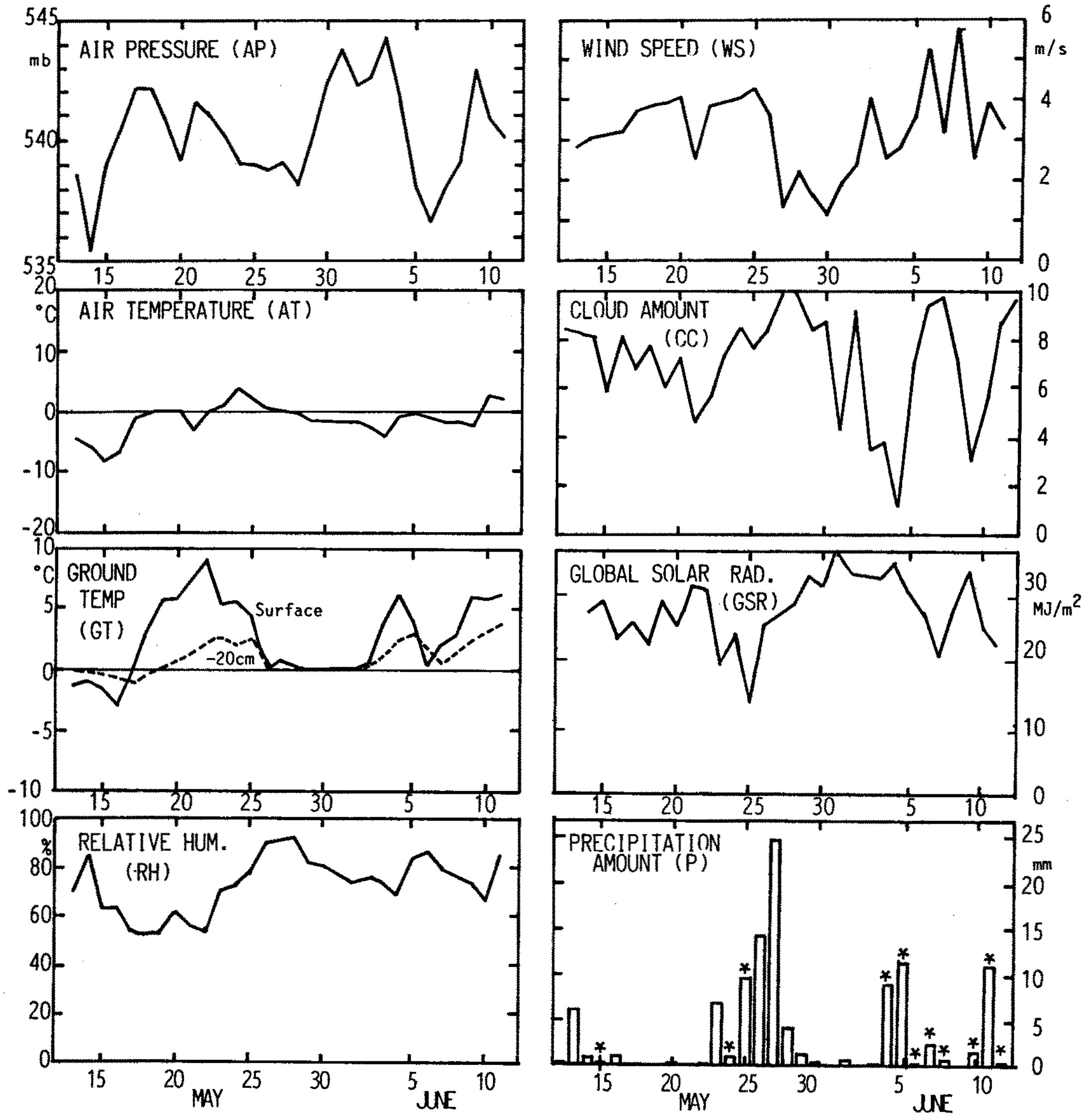

Fig. 3. Daily mean and total values of main meteorological elements.

increased by 43 % from measured value. Considering that part of the precipitation was in form of graupel and small hail, the true value may be a little less than this.

One characteristics of the precipitation process was frequent precipitation from developed cumulonimbus clouds with thunder. The days when precipitation occurred from this type of cloud are shown in Fig. 3 by asterisks. However the most abundant precipitation at the end of May was not of such type. The relative amounts of precipitation in daytime (08:00-20:00) and nighttime (20:00-08:00) were 23 % and 77 %, respectively.

Total precipitation for the same period as BC at adjacent meteorological stations was 65.7 mm at Tuotuo He (4533 m a.s.l., 150 km NNE of BC), 88.3 mm at Amdo (4680 m a.s.l., 90 km SSW of BC). Considering that these values are uncalibrated data, it can be said that there is no marked increase of precipitation in the Tanggula area compared with the surrounding

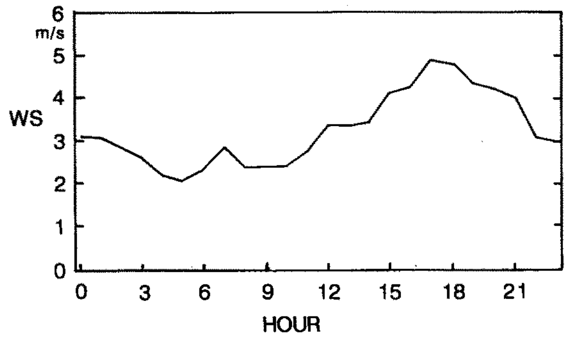

Fig. 4. Mean hourly wind speed for the whole observation period.

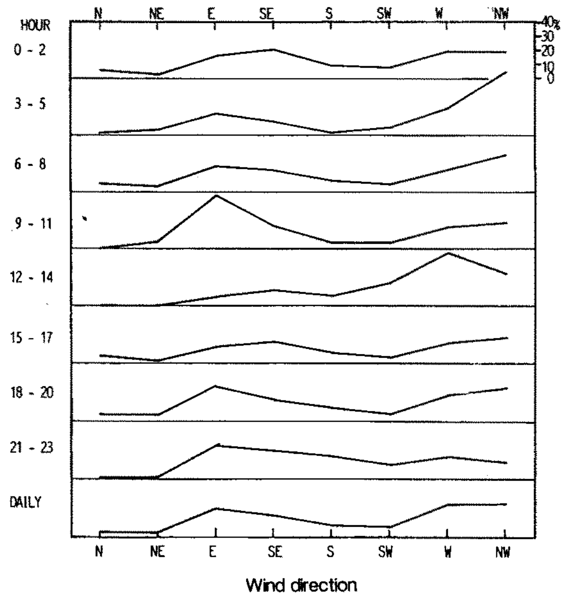

Fig. 5. Frequency distribution of wind direction for eight 3-hour average and daily total.

plain areas. This is different from the conditions observed in the West Kunlun Mountains (Ohata *et al.*, 1987), which showed a large difference between plain areas and the glaciated area.

The precipitation and snow samples were collected for stable isotope and chemical analysis. The $\delta^{18}O$ values of the precipitation samples are shown in Fig. 6. The $\delta^{18}O$ value varied much from -2.9 ‰ to -26.0 ‰ during this period. Low values corresponds to high precipitation period. The $\delta^{18}O$ value became low around May 26 in comparison with previous values, and gradually increased with time. This tendency might be related to the characteristics of water circulation in this region.

2.4 Radiation

Mean daily total global solar radiation was high at 27.3 MJ/m²d as seen in Fig. 3. This is due primarily to the high altitude of this region. The highest value, 37.7 MJ/m²d, occurred on May 31, with daytime mean cloud amount of 4/10. This value was 93 % of the solar radiation at the top of the atmosphere, and shows the occurrence of strong insolation here. The lowest value, 12.0 MJ/m²d, was observed on May 25, with daytime mean cloud cover of 8/10.

2.5 Snow cover

Fig. 7 shows the variation of snow depth and snow covered area. Snow depth (HS) was measured along a 3 m line where snow existed and taking the mean value of them. Snow covered area (AS) was obtained by measuring the existence of snow along a 50 m line approximately perpendicular to the fall line of the

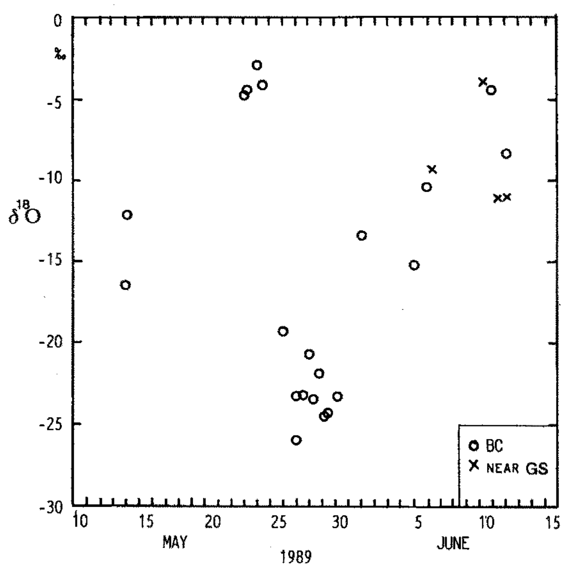

Fig. 6. Variation of $\delta^{18}O$ values of precipitation samples.

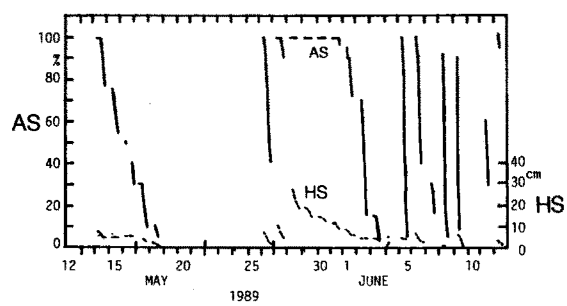

Fig. 7. Variation of snow covered area (AS) and snow depth (HS).

slope, as there were periodic undulations of less than 15 m in this direction. As can be seen from the figure, the main long-lasting snowcover was formed on May 14 and May 28 with 7 and 30 cm depth, respectively. Minor snow cover was also formed at the beginning of June, but it disappeared within a day or two due to melting. One charcteristic of the snow cover here is the long duration of time when snow cover exists in the patchlike condition. The snow cover increased the mean surface albedo over the period to 0.43. In comparison, the albedo on days without snow cover was 0.18 to 0.20.

3. Soil moisture content and evaporation at BC and other sites (Ohta, T.)

3.1. Sites and method of observations

Items observed were soil suction, ground temperature, evaporation from soil and snow surface, and snow melt at the snow surface.

The suction was measured at 3, 15, 30, 36, 48 and 58 cm depth by tensiometers. Automatic recorders were used for 3, 15, 30, 36 cm depth. The data were collected only in the daytime. The soil characteristics were measured for undisturbed soil samples which had a volume of 400 cc. The samples were gathered at 0-4, 12-16, 28-32 and 44-48 cm depth at BC. Samples were also obtained at 10-14 cm on Tanggula Pass (5231 m a.s.l.), AMS-D105 (4990 m a.s.l.) and AMS-D109 (5060 m a.s.l.).

Ground temperatures were measured at 0, 10, 20, 30, 40, 50, 60 and 70 cm depth. The Aanderaa measuring system was used for 0, 10, 20 cm depth and mercury thermometers for the other depths.

Evaporation from soil surface was surveyed by two micro pans whose diameters and depth were 16.5 cm and 7.5 cm respectively. These pans were filled with undisturbed surface soil. The soil of one of the pans was kept under natural condition and the soil of the other was in saturated condition. The latter was used to measure the evaporation potential. These pans were set in the soil, so that the soil surface of the pans and the surrounding ground surface were at the same level. The evaporation was calculated by weighing the change of these pans weights.

Evaporation from snow surface and snow melt in the surface layer were measured by two micro pans. They had the same diameters and depths as in the measurement of evaporation from soil surface. The evaporation was measured using a pan (Pan A) which did not have holes at the bottom. The pan (Pan B) for the measurement of snow melt had many holes, 4.5 mm in diameter at the bottom for the drainage of melt water. The evaporation from snow surface and the snow melt were obtained as follows;

$$Ev = 10 \times dW_A / A \quad (2)$$

$$Mt = 10 \times (dW_B - dW_A) / A \quad (3)$$

where dW_A and dW_B are weight changes of Pan A and Pan B (g/hr), A is the area of the pans (cm^2), and Ev and Mt are the evaporation and the snow melt, respectively (mm/hr.).

It is defined in this report that one day starts from 8:00 BST of the day and ends at 8:00 BST on the next day.

3.2. Results

(1) Soil moisture characteristics

Fig. 8 shows the distributions of porosity (Fig. 8(a)) and saturated permeability (Fig. 8(b)). The porosity is in the range of 0.4-0.6. The order of the

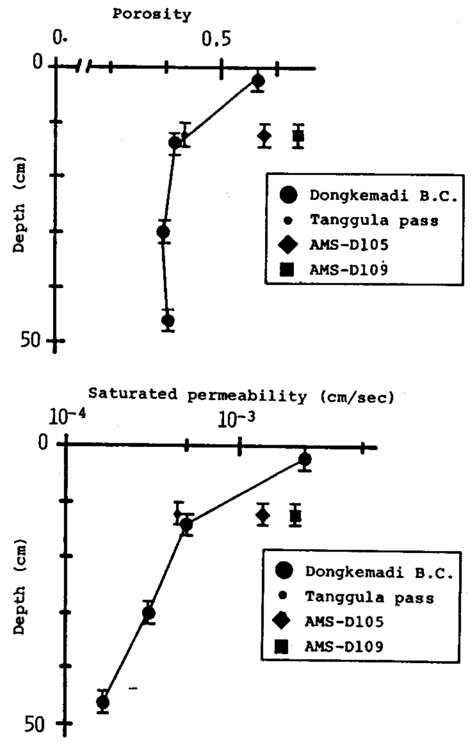

Fig. 8. Porosity and saturated permeability
(a) Distribution of porosity
(b) Distribution of saturated permeability

saturated permeability is from 10^{-4} to 10^{-3} cm/sec. The values decrease abruptly with change of depth from 0 to 10 cm at BC. Values at about 10 cm depth at Tanggula Pass are similar to the values at the BC. On the other hand, values at AMS-D105 and AMS-D109 are larger than at BC.

Fig. 9 shows the relationships between moisture content (θ) and suction (ψ) at the BC. The relationships at 0-4 cm depth are different from the relationships for the layers below 10 cm depth. The relationships between θ and ψ are given by the Klute equation:

$$\theta=\theta_0\frac{\cosh\left(\frac{\psi}{\psi_0}\right)^{\beta}-\frac{\theta_0-\theta_r}{\theta_0+\theta_r}}{\cosh\left(\frac{\psi}{\psi_0}\right)^{\beta}+\frac{\theta_0-\theta_r}{\theta_0+\theta_r}} \quad (3)$$

where θ_0 is porosity, θ is moisture content, ψ is suction, θ_r is moisture content which indicates that soil moisture cannot move under the natural condition, and β and ψ_0 are parameters for the soil moisture characteristics. Table 3 shows the values in Eq. (3) for each depth.

Saturation is defined as follows:

$$S=\theta/\theta_0 \quad (1)$$

Table 3 Parameters obtaimed for Klute equation

Site	Depth	θ_0	θ_r	β	ψ_0
Dongkemadi	0-10 cm	0.57	0.35	-0.25	-900.0
B.C.	12-16 cm				
	28-32 cm	0.41	0.20	-0.20	-1000.0
	44-48 cm				

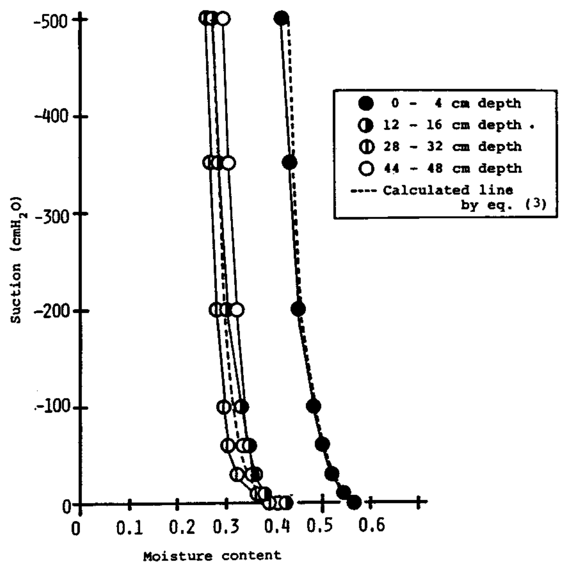

Fig. 9. Relationship between soil moisture content and suction.

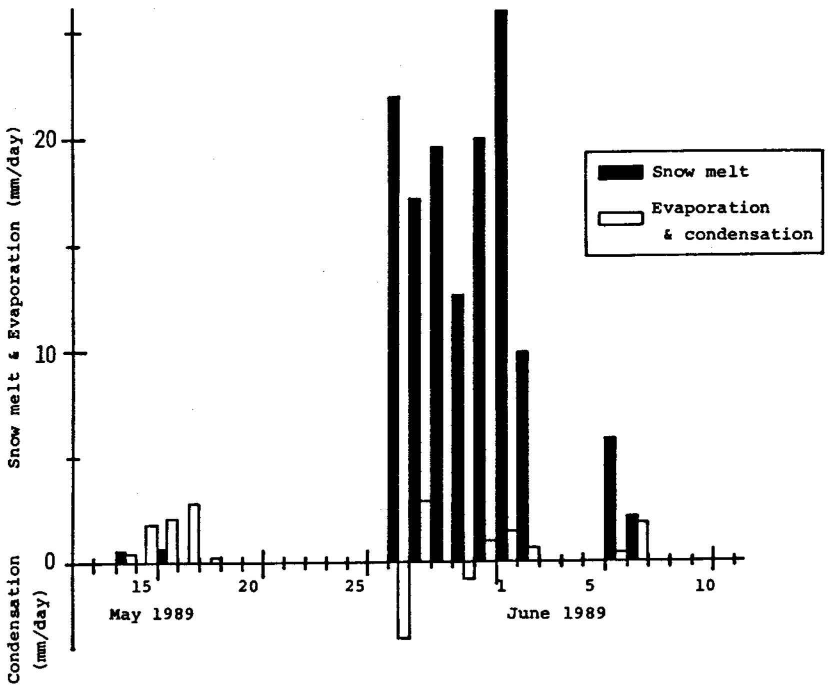

Fig. 10. Daily surface snow melt and daily evaporation from snow surface.

where S is saturation, and θ is moisture content. It is shown in Fig. 9 that the percentage of the fine pores is large at BC. Hence, the saturation is not small when suction is high. It is considered from these results that the saturation was high in the dry season.

(2) Evaporation from snow surface and snow melt

Fig. 10 shows the daily evaporation from snow surface and the daily snow melt. Snow melt scarcely occurred from May 14 to 18, 1989. In this period, snow cover decreased mainly by evaporation. On the other hand, snow melt was high from May 26 to June 2, 1989. The snow cover mainly decreased by snow melt in this period. The soil moisture condition became wet after the snow melt period began.

(3) Changes in soil moisture condition

Fig. 11 shows the changes in saturation at BC. The saturation is obtained from observed values of suction by Eqs. (3) and (4). The saturation became larger after May 26, 1989, because snowmelt began, as described above. But the saturation was more than 0.7 before this snow melt period. So, the saturation was not so low during the winter season and the moisture was high in the permafrost.

It can be noticed in Fig. 11 that the soil was sometimes saturated in the deeper layer and the saturated soil layer became deeper with time. It is con-

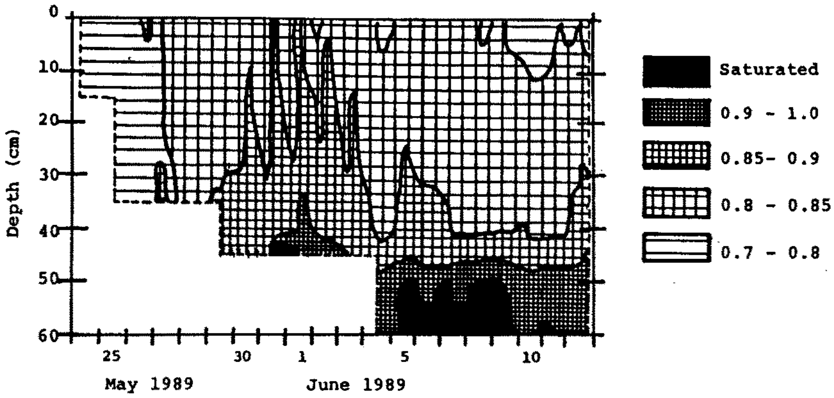

Fig. 11. Change in saturation.

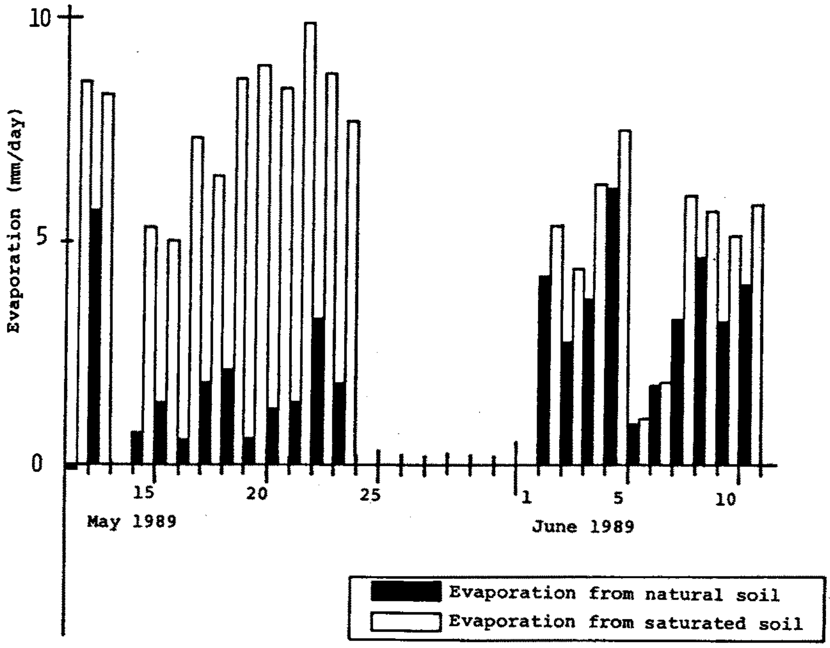

Fig. 12. Daily evaporation from soil surface.

sidered that the permafrost in the deeper layer was very wet, and the permafrost acted as an impermeable layer.

(4) Evaporation from soil surface

Fig. 12 shows the evaporation from saturated soil and natural soil. Evaporation from saturated soil was larger before than after the snowmelt. The meteorological potential for evaporation became smaller after the snowmelt. On the other hand, evaporation from natural soil shows the opposite tendency. Evaporation from natural soil increases with surface soil moisture.

Fig. 13 shows the relationship between the daily mean saturation and the daily evaporation ratios which are ratios of the evaporation from the natural soil to the evaporation from the saturated soil. The evaporation ratio increases with the soil moisture content.

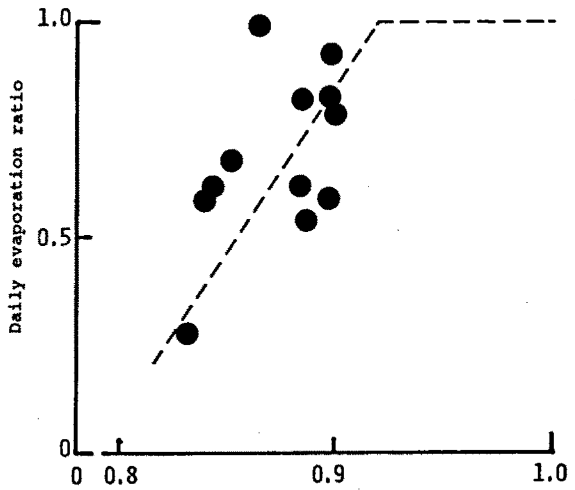

Fig. 13. Relationship between the daily mean saturation and the daily evaporation ratio.

(5) Ground temperature

Fig. 14 shows the changes in the 0 ℃ isothermal line. The permafrost began to melt on May 19, 1989. The active layer depth reached to 70 cm at the end of the observation period.

4. Meteorological observation at GS (Ohno, H.)

In order to investigate the evaporation conditions on Xiaodonkemadi Glacier and to clarify the meteorological elements related to evaporation between the glacier and BC, meteorological observation were carried out in the atmospheric boundary layer on the glacier. The observation site was BS, shown in Fig. 2.

4.1 Observed elements and methods

Observed elements and methods are as follows:

(1) Air temperature: Platinum resistance thermometers in forced ventilating shelters were used. Three of these were set on a observation mast at heights of 30, 60 and 150 cm above the snow surface. The mast height was frequently adjusted as snow surface level changed.

(2) Relative humidity: Capacitance-type humidity sensors with homemade microcapacitance meter were also placed in the shelters. The observation heights were same as those for air temperature. Average

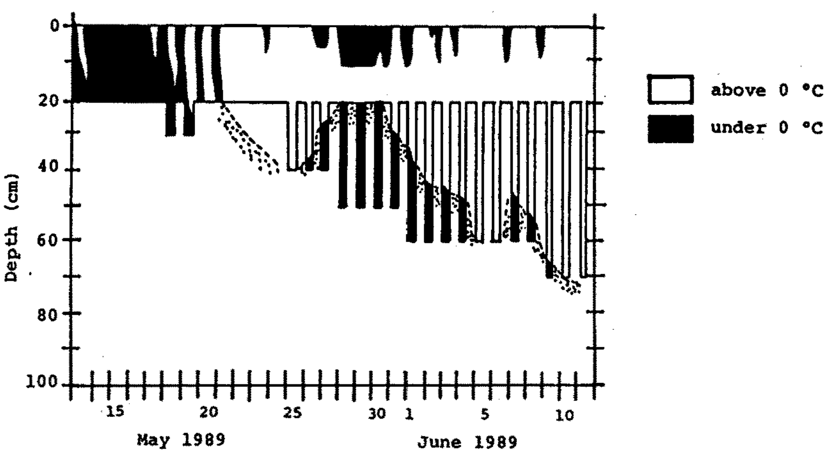

Fig. 14. Changes in the contour line of 0 ℃ of ground temperature.

Table 4 List of instruments and their specifications used at site GS

Element	Sensor txpe	Accuracy	Manufacturer
Air temperature	Platinum resistance in forced ventilated shelter	±0.1℃	Makino Co.
Humidity	Capacitive thin-film type (1518HM) with homemade microcapacitance meter in forced ventilating shelter	———	Vaisala Co.
Wind speed	3-cup anemometer (AC850P)	±0.1m/s	Makino Co.
Wind direction	Potensiometer wind vane (VR036)	3°	Makino Co.
Global solar radiation	Temperature difference type (MS-41)	±2.5%	Eko Co.
Net radiation	Temperature difference type (CN-2)	±3%	Eko Co.
Evaporation	Polystylen vessels (24cm) and	$\pm 2.21\ g\,m^{-2}$	
	Electronic balance (FX6000)		A&D Co.
Surface temperature	Infrared radiative thermometer (ER2008) (Detecting wave length:8.5-12.5μm)	———	National Co.

humidity was obtained due to incoherence between the microcapacitance meters and recorders.

(3) Wind speed: Three 3-cup anemometers were fixed to the mast at heights of 30, 60 and 150 cm above the surface. Wind speed was obtained as 10-minute mean values.

(4) Wind direction: A potentiometer type wind vane was installed at the top of the observation mast (200 cm).

(5) Global solar radiation: A pyranometer was set horizontally on a tripod.

(6) Net radiation: A net radiometer was mounted on a tripod. Nitrogen gas was supplied to the dome from a gas cylinder to preserve the shape of the dome and dryness inside.

(7) Evaporation: Evaporation was measured by weighing two packs of snowfilled polystyrene containers (24 cm in diameter and 12 cm in depth). The weighing was done normally every 30 minutes to the accuracy of 0.1 g by an electronic balance. The snow surface was heated by a hot aluminum plate to form a thin crust, so that the accumulated blown snow can be wiped off before making measurements.

(8) Surface temperature: Surface temperature was ocassionally measured using a handy type infrared radiative thermometer. Measurements were made for ten minutes and the data were averaged. Manual observations of surface temperature and evaporation were carried out from June 9 to 11, 1989.

Instrument specifications are tabulated in Table 4. All data except wind speed were sampled every ten minutes as instantaneous values by a digital data recorder.

4.2 Results

Hourly mean value of air temperature (AT), vapor pressure (VP), global solar radiation (GSR) and net radiation (NR) are shown in Fig. 15. The data of GSR and NR from 19:00 of May 30 to 11:00, June 9 are not available. AT, VP and GSR at GS show similar variations to those at BC. The mean lapse rates for AT and VP between GS and BC were 0.96 ℃/100 m and 0.21 mb/100 m respectively. The mean value of GSR at GS over the period was 88 % of that at BC.

Wind speed (WS) is shown in Fig. 16 along with that at BC. Due to data recorder trouble, these are the only available data. WS at GS was larger than that at BC by 1 to 2 m/s. The correlation coefficient for WS at GS and BC is higher when taking 10-minute previous values for BC than when taking

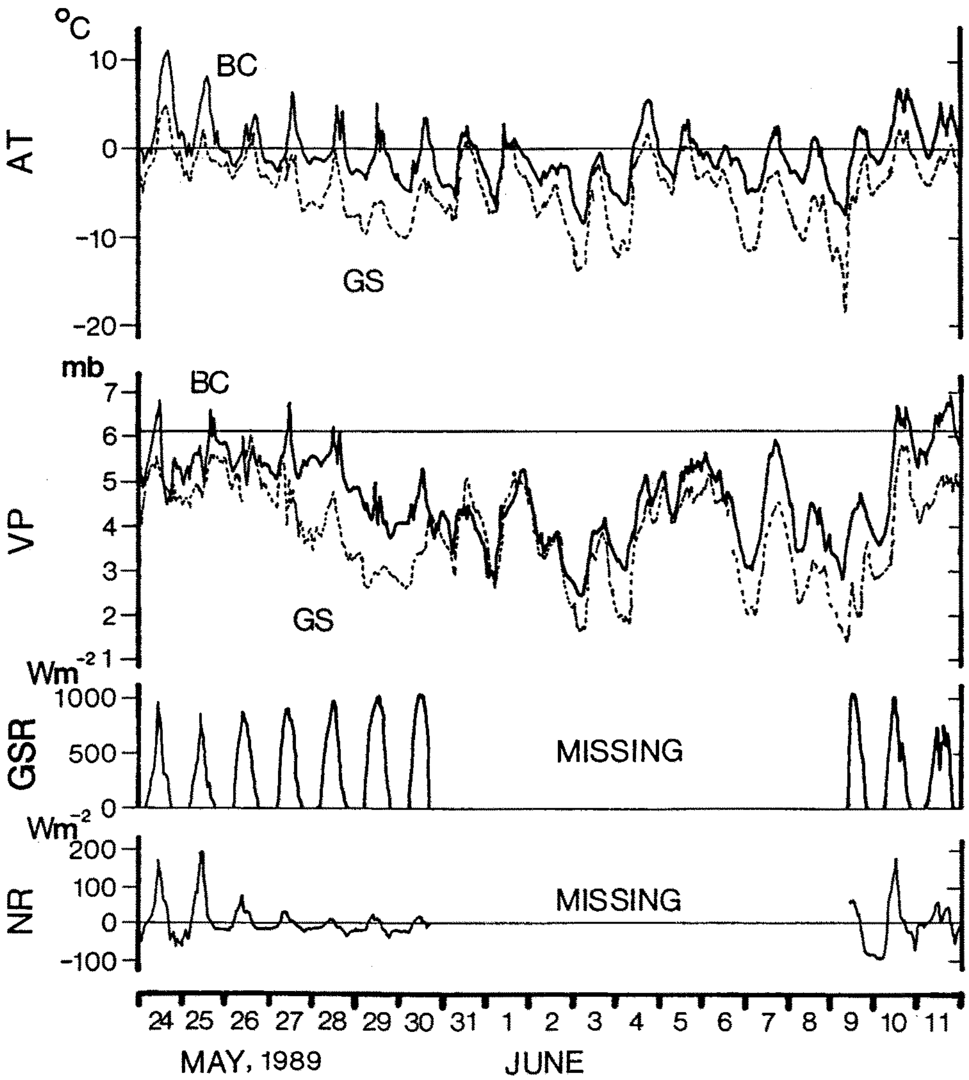

Fig. 15. Observed meteorological elements on GS from May 24 to June 11, 1989. For comparison, air temperature (AT) and vapor pressure data at BC are drawn as solid lines.

simultaneous values.

Wind direction (WD) is shown in Fig. 17. Frequent E to S winds were observed. Besides the long term variation, frequent short term counterclockwise rotation in WD is found.

The evaporation rate and firn surface temperature were measured in daytime from June 9 to 11, 1989. Fig. 18 shows the evaporation rate. Although solid precipitation frequently occurred, evaporation was predominant.

5. Automatic meteorological observations (Ohata, T.)

Two automatic meteorological observation sites were set up at D105 and D109 shown in Fig. 1. At the former site, it was set at 2 m above the ground surface approximately 20 m from the Qinghai-Xizang Highway (Tibet Highway), and was maintained by local Tibetan people. The latter one was set above the roof of a building approximately 5 m above the ground surface, and was maintained by an official in

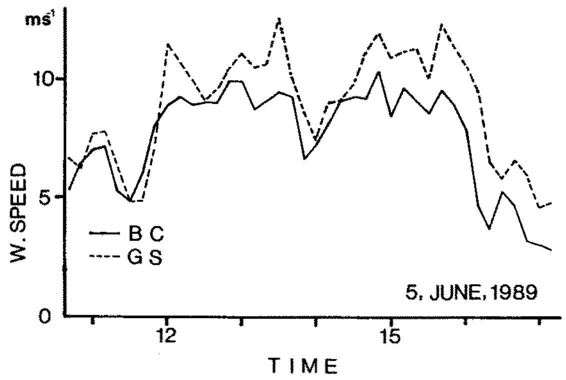

Fig. 16. Wind speed at site GS on June 5, 1989. For comparison, data at BC is also shown..pa

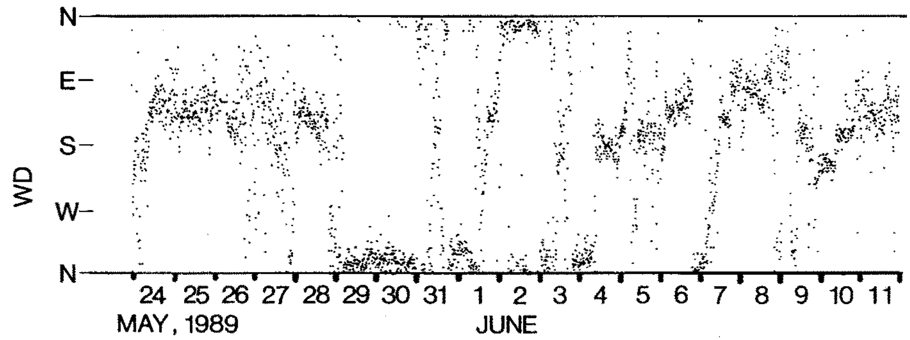

Fig. 17. Wind direction at GS from May 24 to June 11, 1989.

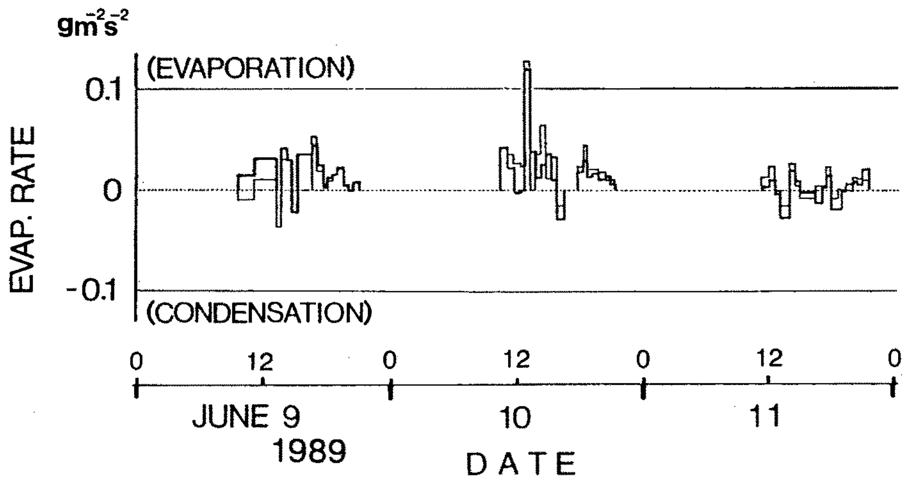

Fig. 18 Evaporation rate at GS from June 9 to 11. The bold line and thin line indicate the result for container 1 and 2, respectively.

the road maintainance office. Observed elements were air temperature, relative humidity, global solar radiation, wind speed and wind direction.

Furthermore, the station at D105 was left there for further continuous observation. The number of sensors was increased on June 12, so that reflected solar radiation, surface and ground temperature and air pressure could be measured. They were checked in October, 1989 by H. Furukawa, and found to be working quite well, with only slight trouble with the air temperature sensor. In April 1990, H. Ohno revisited that site and recovered the data, and confirmed that they worked quite well. The station is planned to be maintained at least for the following couple of years.

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Appendix 1
Table of daily mean/total values of meteorological elements at B.C.

Elements	Type of data
WS : Wind speed	mean
WD : Wind direction	most frequent direction
AP : Air pressure	mean
GSR : Global solar radiation	total
AT : Air temperature	mean
RH : Relative humidity	mean
GT : Ground temperature (surface, -10cm and -20cm)	mean
CC : Daytime cloud amount	mean
P : Precipitation amount (calibrated)	total,08:00-08:00 Next day
HS : Snow depth	08:00
AS : Area of snow coverage	08:00

DATE	WS m/s	WD	AP mb	GSR MJ/m²	AT (2m) ℃	RH (2m) %	GT surf ℃	GT -10cm ℃	GT -20cm ℃	CC /10	P mm	HS cm	AS %
05/13	2.8	E	538.6	15.0	-4.6	70	-1.4	-0.2	-0.3	8.4	5.0		
05/14	3.1	NE	535.4	28.2	-6.0	85	-1.0	-0.2	-0.4	8.2	0.6	7.5	100.0
05/15	3.1	NW	539.0	27.3	-8.4	63	-1.6	-0.6	-0.5	5.8	0.1	4.5	75.0
05/16	3.2	W	540.5	23.2	-6.9	64	-3.0	-1.1	-0.8	8.2	0.9	5.0	50.0
05/17	3.7	W	542.2	26.1	-1.4	53	-0.4	-1.1	-1.1	6.8		4.0	30.0
05/18	3.8	W	542.1	17.4	-0.4	52	3.2	0.2	-0.6	7.8		2.0	10.0
05/19	3.9	W	540.7	26.1	-0.1	53	5.6	1.3	0.0	6.0			
05/20	4.1	W	539.1	24.7	0.0	62	5.8	2.2	0.7	7.3	0.1		
05/21	2.5	W	541.6	29.0	-3.3	56	7.3	2.5	1.2	4.6			
05/22	3.8	NE	541.0	29.6	-0.2	53	9.1	3.5	2.1	5.6	0.1		
05/23	3.9	NE	540.2	16.9	0.9	71	5.2	3.3	2.5	7.4	6.9		
05/24	4.0	SW	539.0	28.6	3.7	72	5.6	2.9	2.0	8.6	0.9		
05/25	4.3	SW	539.0	12.0	2.2	78	4.5	3.2	2.5	7.6	9.6		
05/26	3.6	SW	538.8	29.4	0.4	89	0.4	0.9	1.1	8.4	14.2	7.0	100.0
05/27	1.3	NW	539.1	29.0	0.0	91	0.8	0.1	0.1	10.0	24.9	10.5	100.0
05/28	2.2	SW	538.2	29.5	-0.4	92	0.3	0.0	0.0	10.0	4.1	27.5	100.0
05/29	1.5	NW	540.1	33.3	1.7	82	-0.1	0.0	0.0	8.4	1.2	18.5	100.0
05/30	1.1	SW	542.4	33.2	-1.7	81	-0.1	0.0	0.0	8.8	0.2	14.5	100.0
05/31	1.8	W	543.9	37.7	-1.8	77	0.0	0.1	0.0	4.2		11.5	100.0
06/01	2.4	NE	542.3	34.6	1.7	74	0.0	0.2	0.0	9.2	0.5	8.0	95.0
06/02	4.0	NW	542.6	28.1	-1.4	75	0.5	0.4	0.2	3.4		4.5	70.0
06/03	2.5	NE	544.4	32.8	-3.3	73	3.8	1.8	1.0	3.8	0.1	4.5	15.0
06/04	2.8	NE	541.5	35.8	0.0	68	6.2	3.3	2.3	1.0	8.8	1.0	5.0
06/05	3.6	NW	538.1	28.8	0.2	83	4.0	3.3	3.0	7.2	11.3	4.0	100.0
06/06	5.2	W	536.6	29.1	-0.5	86	0.1	1.3	1.6	9.4	0.2	7.0	100.0
06/07	3.2	E	538.1	16.9	-1.2	79	2.2	0.8	0.4	9.8	2.2	2.5	40.0
06/08	5.8	W	539.2	26.6	-1.2	77	3.0	2.0	1.4	7.2	0.5	0.5	90.0
06/09	2.5	NE	542.9	35.5	-1.7	74	6.1	3.5	2.5	3.0		0.5	90.0
06/10	3.9	E	540.8	27.5	3.1	67	5.8	3.7	3.2	5.4	1.6		
06/11	3.3	W	540.1	26.0	2.6	85	6.2	4.5	3.7	8.6	10.9	0.5	90.0

Appendix 2 Porosity and saturated permeability

Site	Depth	θ_0	Ks (cm/sec)
Dongkemadi	0 − 4 cm	0.596	2.36×10^{-3}
B.C.	12−18cm	0.421	5.05×10^{-4}
	28−32cm	0.397	3.03×10^{-4}
	44−48cm	0.412	1.78×10^{-4}
Tanggula pass	10−14cm	0.434	4.46×10^{-4}
AMS-D105	10−14cm	0.578	1.36×10^{-3}
AMS-D109	10−14cm	0.646	2.09×10^{-3}

Appendix 3 Daily evaporation and snow melt + : evaporation or melt − : condensation

Date		Evaporation from soil natural (mm/day)	Evaporation from soil saturated (mm/day)	Evaporation from snow evaporation (mm/day)	Melt snow melt (mm/day)
5	12	-0.01	8.64		
	13	5.71	8.28		
	14			0.55	0.60
	15	0.74	5.33	1.93	0.10
	16	1.42	5.06	2.94	0.70
	17	0.59	7.37	2.94	0.0
	18	1.85	6.49	0.26	0.0
	19	2.20	8.65		
	20	0.61	8.99		
	21	1.28	8.46		
	22	1.41	9.79		
	23	3.29	8.78		
	24	1.86	7.71		
	25				
	26				
	27			-3.58	22.00
	28			2.94	17.20
	29			0.03	19.65
	30			-0.81	12.56
	31			2.00	20.06
6	1			1.44	26,32
	2	4.25	5.39	0.66	9.93
	3	2.77	4.39		
	4	3.71	6.30		
	5	6.19	7.51		
	6	0.94	1.07	0.43	5.85
	7	1.79	1.81	1.88	2.20
	8	3.28	6.06		
	9	4.66	5.69		
	10	3.23	5.32		
	11	4.03	5.85		

Appendix 4 Ground temperature at 15:00 B.S.T

Date	Depth (cm) 30	40	50	60	70	comment
5 25	0.7	-0.4				
26	0.2	-0.4				
27	-0.1	-0.4				
28	-0.2	-0.3	-0.5			
29	-0.4	-0.5	-0.7			
30	-0.3	-0.4	-0.6			
31	-0.3	-0.4	-0.5			
6 1	-0.3	-0.2	-0.6	-0.5		
2	0.5	0.1	-0.6	-0.3		
3	0.4	0.0	-0.4	-0.3		
4	0.4	0.2	-0.2	0.0		
5	1.7	0.8	0.4	0.4		*18 : 00 B.S.T
6	1.0	0.6	0.4	0.4		
7	1.3	-0.3	-0.4	-0.3		
8	2.1	-0.1	-0.2	0.0		
9	2.5	0.1	-0.1	0.1	-0.5	
10	4.4	1.3	0.7	0.8	-0.1	*18 : 00B.S.T
11	4.5	1.4	0.9	1.2	0.0	
12	5.0	1.5	1.1	1.4	0.3	*18 : 00 B,S.T