チベット高原において観測された凍土の深さと積雪重量（英文）

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Frost Depth and Snow Weight Observed in the Tibetan Plateau

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Abstract

Automatic observations of frost depth and snow weight (water equivalent of snow) were carried out at Lhasa, Rikeze and Nagqu in the Tibetan Plateau from July 1993 to March 1999. Based on the observation data together with routinely measured data from the meteorological stations, the features of frozen ground and snow cover were elucidated. The relationships between air temperature, precipitation and snow cover were also analyzed.

The frozen ground was not thick at Lhasa and Rikeze. The features of frozen ground at Nagqu are as follows : In winter, excluding midwinter, the frozen ground near the surface sometimes showed diurnal change, that is, it froze during the night and melted during the day. The frost penetration began in October and continued until the middle of March. The maximum frost depth, depending on winter meteorological conditions, ranged from 160 to 200 cm across the six winters. The efficiency of frost penetration increased with the amount of precipitation in the preceding summer. These can be said to be the features of frozen ground in dry and seasonally frozen ground regions.

Snow cover was hardly observed at Lhasa and Rikeze. The features of the snow cover at Nagqu are as follows: Snow cover did not last for a whole winter. The number of days of snow cover was 27 to 85 days and the snow depth did not exceed 10 cm from the winter of 93/94 through the winter of 97/98. The snow weight was less than 20 kg/m^2 and the snow density was 0.05–0.4g/cm^3 (the average was 0.2g/cm^3).

The obtained relationships between air temperature, precipitation and snow cover are as follows : During six years, the winter air temperature negatively correlated to the number of days of snow cover at Nagqu. Warm (cold) winters tended to follow wet (dry) summers with much (little) precipitation respectively. The precipitation from June through September negatively correlated to that in May. However, their statistical significance cannot be discussed due to the short duration of the analysis (6 years).

Key words : Frozen ground, Frost depth, Snow cover, Snow weight, Tibetan Plateau

1. Introduction

The Asian monsoon (Indian monsoon and East Asian monsoon) forms the natural environment and influences the daily lives of people across the Asian region including Japan. Recently, the Asian monsoon has been considered to be one component of the general circulation, and the research on its relationship with other large scale phenomena such as ENSO events and on its role in the global climate system is being undertaken extensively. Therefore, research on the Asian monsoon is one of the important subjects of meteorology.

Since Hahn and Shukla (1976) revealed that the extent of the Eurasian snow cover negatively correlated to Indian monsoon rainfall, their relationship has been analyzed by some researchers (e.g. Dickson, 1984 ; Morinaga, 1992), and the effects of snow cover on atmospheric circulation have also been investigated using GCM (e.g. Yasunari *et al*., 1991 ; Vernekar *et al*., 1995). Snow cover reflects solar radiation well and reduces the net radiation (albedo effect) and it also moistens the ground after it melts (snow-hydrological effect). Although both effects reduce the ground surface temperature and suppress atmospheric heating, the albedo effect is dominant in spring and the snow-hydrological effect is significant in summer.

The frozen ground preserves the soil moisture as ice during the winter, which means that the frozen ground delays the climate signal in autumn until the subsequent spring. In the permafrost region, the frozen soil remaining in the ground acts as a permeable layer in the warm season, which controls the circulation of water.

The Tibetan Plateau is a huge mountainous area in the Eurasian continent with an altitude of about 4500 m on average. It acts as a heating source for the free atmosphere in summer and is a dynamic obstacle for the airflow. The snow cover and frozen ground over the Tibetan Plateau are expected to affect the Asian monsoon activity. In order to investigate the relationships between the snow cover and frozen ground over the Tibetan Plateau and the Asian monsoon, satellite data is useful since it provides data on snow cover, convective activity and precipitation distributions across a wide area (e.g. Ueno, 1998 ; Yazaki, 1999). Although the remote sensing technique still requires ground truth data for validation, the routine data from the meteorological stations in the Tibetan Plateau has not been sufficient for this purpose.

In this study, instruments to automatically observe the frost depth and snow weight (water equivalent of snow) were deployed at three sites in the Tibetan Plateau and continuous observations were carried out from the summer of 1993 to the spring of 1999. The features of frozen ground and snow cover will be shown in the following on the basis of the observations and analysis of collected routine meteorological data.

2. Methodology

2.1 Sites and observations

The observation sites are Lhasa, Rikeze and Nagqu, which are located in the eastern part of the Tibetan Plateau. These sites are shown in Fig. 1 together with the meteorological stations belonging to the Tibet Autonomous Meteorological Bureau. The locations and altitudes of the three sites are summarized in Table 1. The topography of Lhasa, Rikeze and Nagqu is characterized as the bottom of a valley, the bottom of a basin and a gentle hill, in that order. There are permafrost regions and seasonally frozen ground regions in the Tibetan Plateau, and the three sites are all located in the latter region.

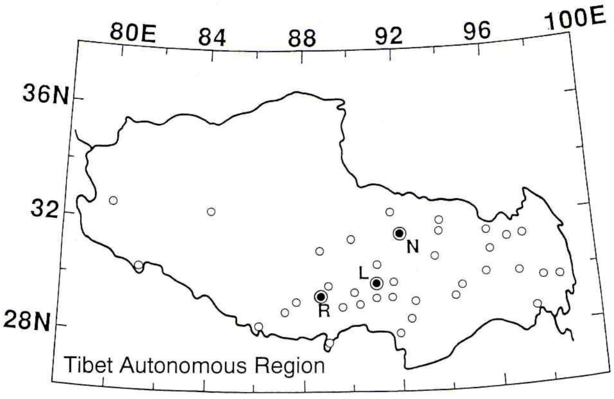


Fig. 1 Locations of observation sites (L : Lhasa, R : Rikeze, N : Nagqu) and meteorological stations belonging to the Tibet Autonomous Meteorological Bureau (○).

Table 1 Locations and altitudes of observation sites.

Site	Long.(E)	Lat.(N)	Altitude(m)
Lhasa	91°08′	29°40′	3649
Rikeze	88°53′	29°15′	3836
Nagqu	92°04′	31°29′	4507

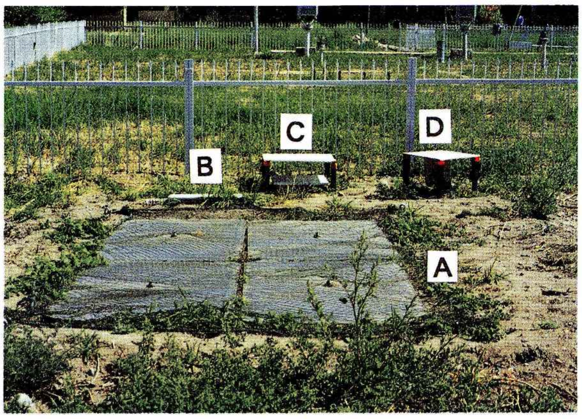


Photo 1 Snow weight meter (A-C) and frost depth meter (D) at Lhasa.
A : metal wafer units, B : pressure sensor, C : container box.

The instruments were set at the three sites and continuous observations commenced in July 1993. At every site, frost depth meter and snow weight meter were set in the precinct of the meteorological station for convenience of maintenance (Photo 1). The Meteorological Research Institute installed Automatic Weather Stations for micrometeorological observations at the same sites. Visual inspection of the instruments was carried out every month by the staff of the meteorological station. Data was collected twice a year, in principle, using a personal computer.

Since significant snow weight was not recorded and the frozen ground did not become thick at Lhasa and Rikeze, the observations at these two sites were terminated in the summer of 1996. The observations are summarized in Table 2.

2.2 Frost depth meter

The frost depth meter (FDM2) consists of a sensor and a controlling and recording unit built into a box. The sensor unit is inserted into a plastic protection pipe, which is connected to the box. The sensor is buried in the ground and the box is placed on the ground surface. As shown in Fig. 2, the sensor unit of the FDM2 is an FRP pole, 225 cm long and 1.6 cm in diameter, enclosed in a Silicon rubber tube. The space between the FRP pole and the tube is filled with deaerated water. The thickness of the water is about 1 mm. The sensor unit has 104 electric terminals, separated from each other by 2 cm, to detect the freezing of the deaerated water around the terminals by measuring the resistance between the detection terminals and the one common terminal. The scanning is conducted every two hours and the results are stored in an EPROM.

Table 2 Summary of observations.

	Frost Depth			Snow Weight		
Winter	Lhasa	Rikeze	Nagqu	Lhasa	Rikeze	Nagqu
93/94	×	○	○	○	○	○
94/95	×	○	○	○	○	○
95/96	○ *1	× *1	○ *1	○	○	○
96/97	—	—	○	—	—	○ *2
97/98	—	—	○	—	—	○
98/99	—	—	○	—	—	○

○ : Observed.
× : Not observed due to sensor trouble.
— : No observation.
*1 : Sensor was changed from the FDM2 to the FDM3.
*2 : Pt resistance thermometer was added.

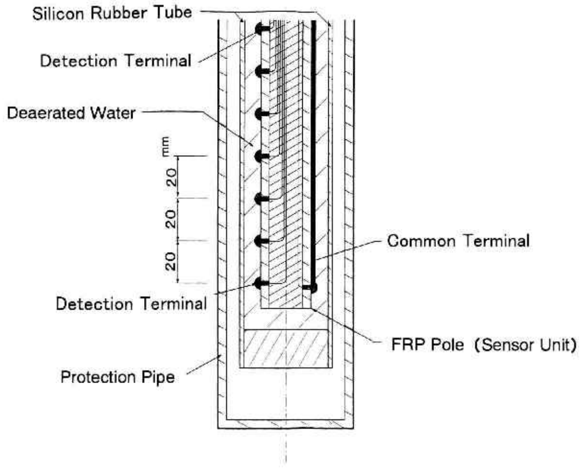


Fig. 2 Sensor of the frost depth meter (FDM2).

In July 1995, the frost depth meter was changed from the FDM2 to the FDM3, whose scanning method and sensor structure had been changed. However, the principle of the measurement is the same. The structure of the FDM3 sensor unit is shown in Fig. 3. A soft PVC tube filled with deaerated water is attached to the board. One sensor unit has 16 detection terminals in the deaerated water at intervals of 2 cm. And seven units are connected and inserted into the protection pipe to obtain a record from the ground surface to the depth of 2 m. The state of the deaerated water (water/ice) is detected by scanning every detection terminal.

2.3 Snow weight meter

The snow weight meter to measure the weight (water equivalent) of accumulated snow is shown in Fig. 4, which is the same as that commonly used in Japan (Kimura, 1983). Four metal wafer units filled with anti-freeze are placed on the ground to support the accumulated snow. The snow on the metal wafer units results in a change of the inner pressure within the units, which is detected by the pressure sensor connected to the metal wafer units with copper pipes. Pressure change is converted to snow weight value and recorded in a data logger every hour. The ground temperature just below the metal wafer unit is measured by a Pt resistance thermometer. From the winter of 96/97, another Pt resistance thermometer was added at Nagqu to measure the temperature near the pressure sensor (hereafter, called the box temperature). These temperatures are also recorded in a data logger.

The snow weight meter used is suitable for the heavy snow cover in warm areas, such as in Japan. Under such conditions, the temperature at the ground

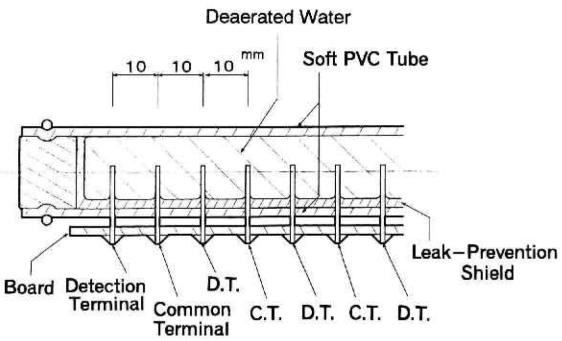


Fig. 3 Sensor unit of the frost depth meter (FDM3).

surface under the accumulated snow is almost 0°C and it is not necessary to consider the temperature dependence of the snow weight meter. In the Tibetan Plateau, except for high mountainous areas, however, the snow is not as heavy as in the snowy regions of Japan and the temporal variation of the ground temperature is large. This requires data correction to obtain reliable snow weight values.

After examining the variations of apparent snow weight, which corresponds to the output voltage of the snow weight meter when there was no snow cover, it was found that apparent snow weight has thermal hysteresis. It is impossible to correct the snow weight values by taking fully the hysteresis into account. In this study, a regressive relationship between the apparent snow weight and one of three kinds of temperatures, that is, air temperature, ground temperature or box temperature, was obtained from the data when there was no snow cover. In order to avoid the effect of thermal hysteresis, daily averaged values of apparent snow weight and temperature were principally used. Instantaneous values in the afternoon (09Z) were used exceptionally in some periods of 96/97, 97/98 and 98/99 winters. By using the regressive relationship, the corrected snow weight was obtained as a daily value.

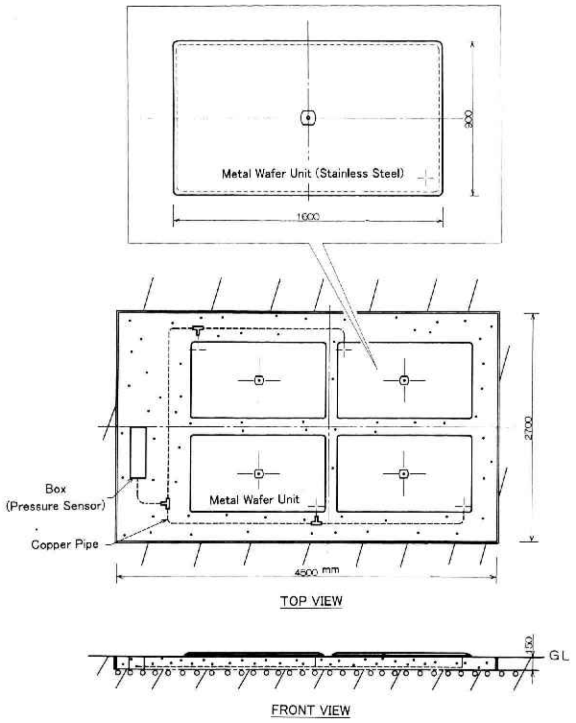
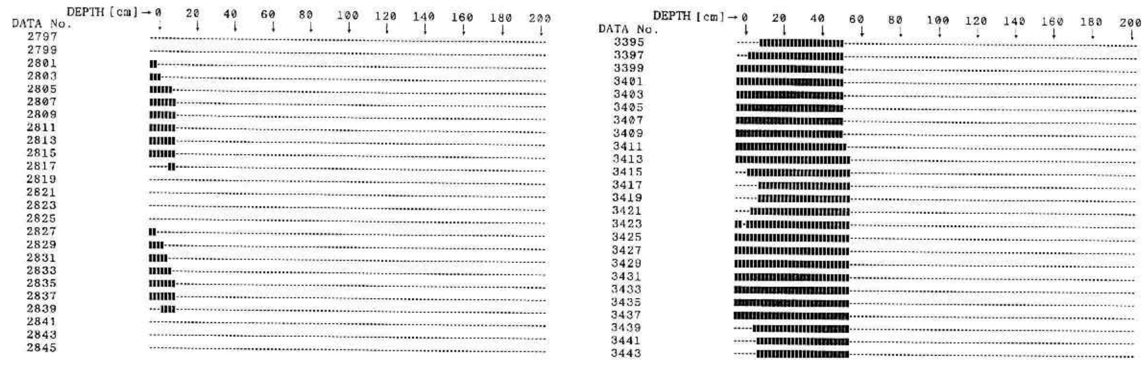


Fig. 4 Snow weight meter.

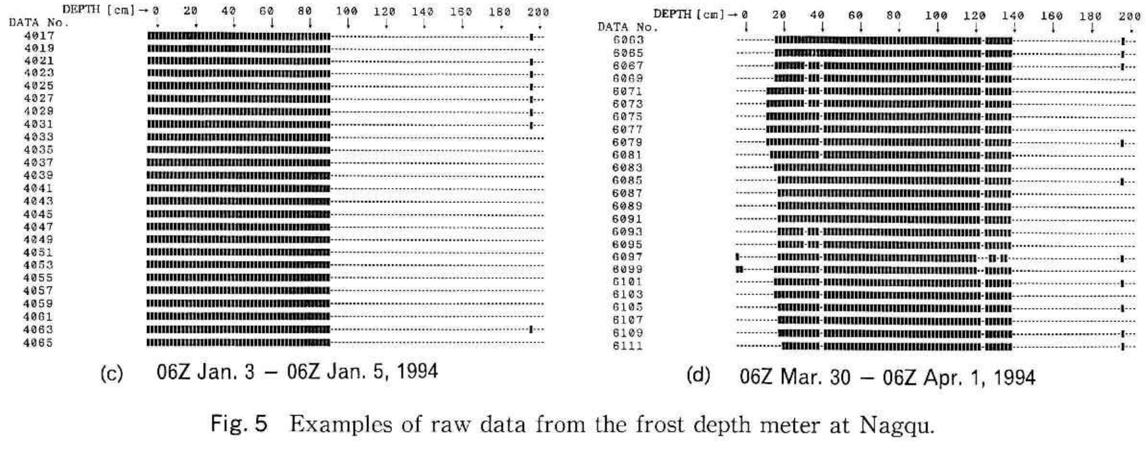
3. Results

3.1 Frost depth

Examples of raw data from the frost depth meter at



(a) 06Z Nov. 16 – 06Z Nov. 18, 1993 (b) 06Z Dec. 8 – 06Z Dec. 10, 1993



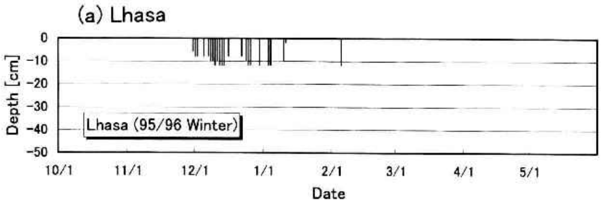
(c) 06Z Jan. 3 – 06Z Jan. 5, 1994 (d) 06Z Mar. 30 – 06Z Apr. 1, 1994

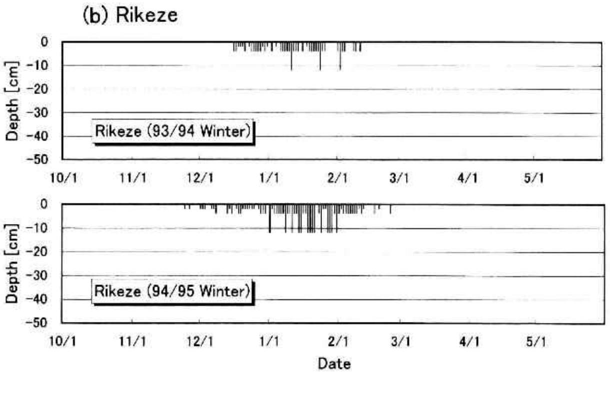
Fig. 5 Examples of raw data from the frost depth meter at Nagqu.

Nagqu are shown in Fig. 5, which includes four different stages of frost penetration. The black mark indicates a frozen portion of the ground. The local time at Nagqu is GMT+6hours and the diurnal variations of frozen ground can clearly be seen in the figures. In the early stage (Fig. 5(a)), the ground near the surface froze only at night. Thereafter, the frozen ground extended downward (Fig. 5(b)), but the layer near the surface melted during the day. In the midwinter, the frozen ground did not melt even during the day (Fig. 5(c)), and in spring, the ground near the surface melted and the frozen portion was left underground (Fig. 5(d)).

Figure 6 shows the seasonal variations of the frozen ground observed at the three sites (Lhasa, Rikeze and Nagqu) from the winter of 93/94 through the winter of 98/99, where the black bar illustrates the daily maximum frost depth registered from 04Z of the previous day to 02Z. Some meteorological stations in the Tibet Autonomous Region routinely measure frost depth. Their instrument is a rubber tube of about 1 cm diameter, and is filled with water. They pull up the tube and measure the length of the frozen portion every morning (00Z). The routine data corresponding to the observation periods at the three sites are shown in Fig. 7, where another frozen ground layer near the surface was observed in the spring at Nagqu except for in 1996 and 1998. At Nagqu, the routine data of frost depth in April and May 1999 is not illustrated.

The seasonal change of the frozen ground at Nagqu in the winter of 93/94 is as follows: At the beginning of the winter, the soil layer near the surface froze during the night and melted during the day, and the daily maximum frost depth did not increase. At this stage, the FDM2 was sometimes unable to detect a thin frozen ground layer. From the middle of November to the end of January, the frozen ground extended and the observed data coincided with the routine data. After that, the observation indicates that the depth of the frozen ground increased until the beginning of March and the frost depth attained its maximum (158 cm). However, the routine data shows that the penetration continued until the middle of March and the maximum frost depth was 200 cm. In spring, the





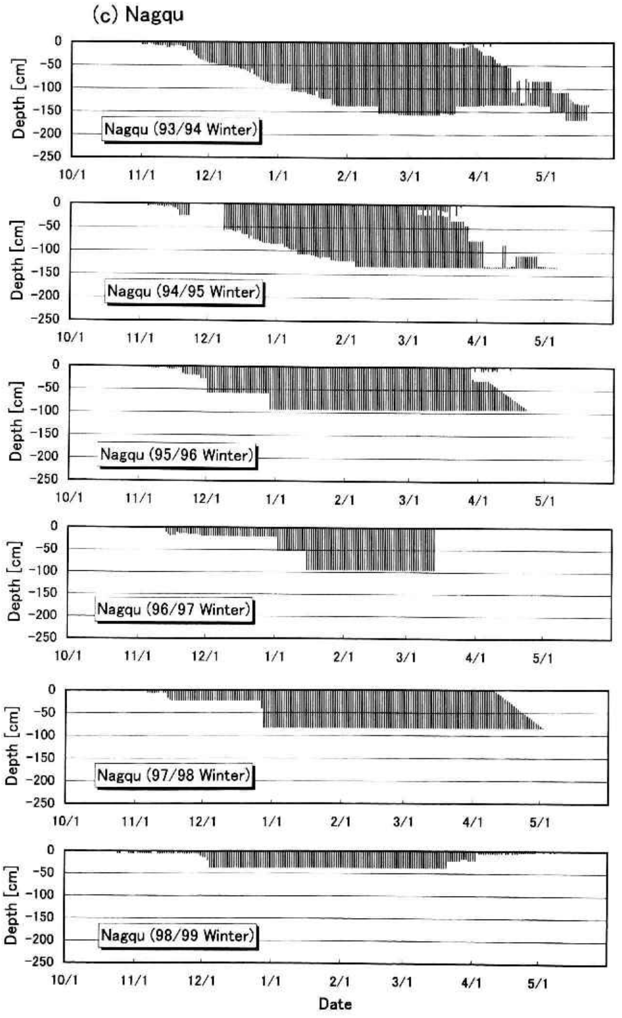


Fig. 6 Seasonal variation of the frozen ground (observations).
(a): Lhasa, (b): Rikeze and (c): Nagqu.

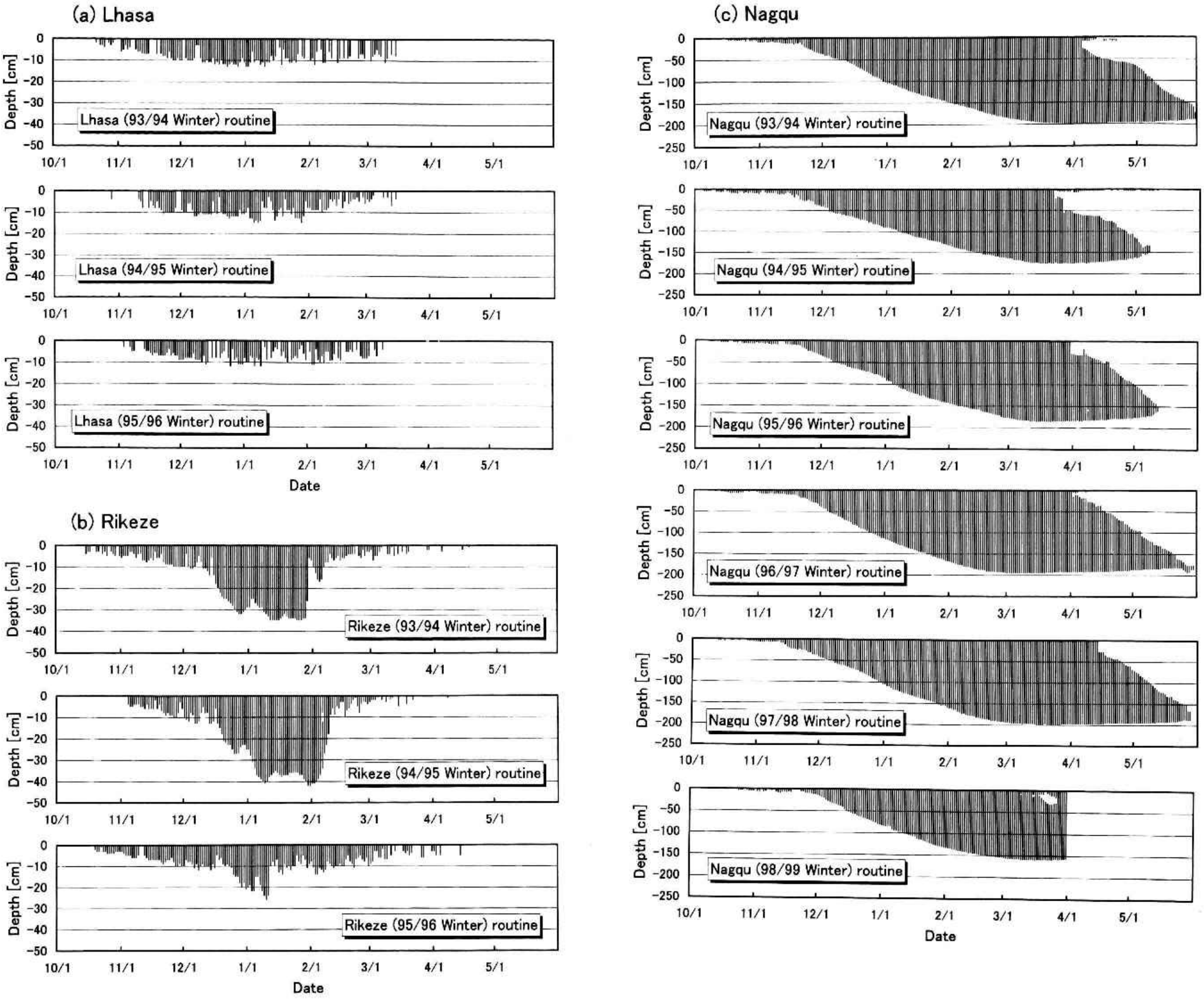


Fig. 7 Seasonal variation of the frozen ground (routine measurements).
(a) : Lhasa, (b) : Rikeze and (c) : Nagqu.

frozen soil melted rapidly from the surface downward. This comparison shows that the observation is highly concordant with the routine data before midwinter but that this is not so after midwinter. The data at Nagqu in the winter of 94/95 shows a similar tendency to that seen in the winter of 93/94.

In July 1995, the instrument was changed from the FDM2 to the FDM3 at the three sites. The underestimation of the maximum frost depth observed with the FDM3 was more serious than that with the FDM2.

Both the FDM2 and the FDM3 results show stepwise changes of the frozen portion of the ground. The FDM2 scans the resistance between the detection and common terminals by eight paired terminals. The stepwise changes may be due to this scanning method. The sensor of the FDM3 consists of separated units, which may be another reason why the frozen portion shows stepwise changes.

The maximum frost depths at Lhasa, Rikeze and Nagqu are summarized in Table 3. At Rikeze, the observed frost depth with the FDM2 was smaller than the routine data in the winters of both 93/94 and 94/95. This deficiency might be due to the structure of the frost depth meter, that is, a box is placed on the ground surface and the sensor is connected to it. In the case of thin frozen ground, the downward heat conduction through the sensor from the ground surface might affect the temperature distribution in the sensor and disturb the accuracy of the observation.

The discrepancies between the observation and the routine data in the mature and thawing stages will be discussed in the following. An example of the soil temperature profile, which was routinely measured at Nagqu, is shown in Fig. 8. The discrepancies may partly be due to the fact that the ground temperature between the depths of 40 cm and 160 cm at mature and

Table 3 Summary of accumulated freezing index (I), maximum frost depth (D), coefficient α and precipitation (R) in the preceding summer (Jul.-Sep.). Values are routinely measured.

Winter	I [deg*day]	D [cm]	α	R [mm]
(Lhasa)				
93/94	80	13	1.5	420
94/95	134	15	1.3	279
95/96	58	12	1.6	389
96/97	157	19	1.5	280
97/98	93	11	1.1	196
98/99	110	15	1.4	424
(Rikeze)				
93/94	276	35	2.1	302
94/95	330	42	2.3	199
95/96	176	26	2.0	308
96/97	349	50	2.7	349
97/98	222	33	2.2	203
98/99	271	39	2.4	479
(Nagqu)				
93/94	1296	200	5.6	348
94/95	1538	177	4.5	115
95/96	1249	186	5.3	352
96/97	1463	195	5.1	222
97/98	1164	199	4.9	251
98/99	1130	160	4.8	373

Note : I was obtained from air temperature.

thawing stages was close to 0°C and its vertical gradient was very small. In this situation, small disturbances to the ground and/or sensor temperature would affect the detection of the frozen portion. This is more remarkable for the FDM3 with separated units than for the FDM2.

3.2 Snow weight (water equivalent of snow)

Figure 9 shows the time series of snow depth at the three sites from July 1993 to May 1998, which was

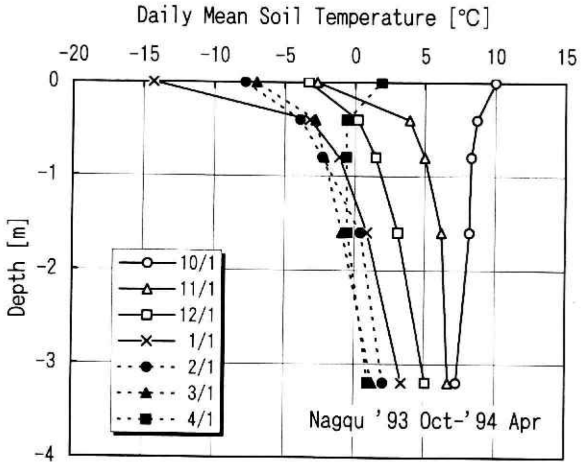


Fig. 8 Profiles of daily mean soil temperature at Nagqu (winter of 93/94).

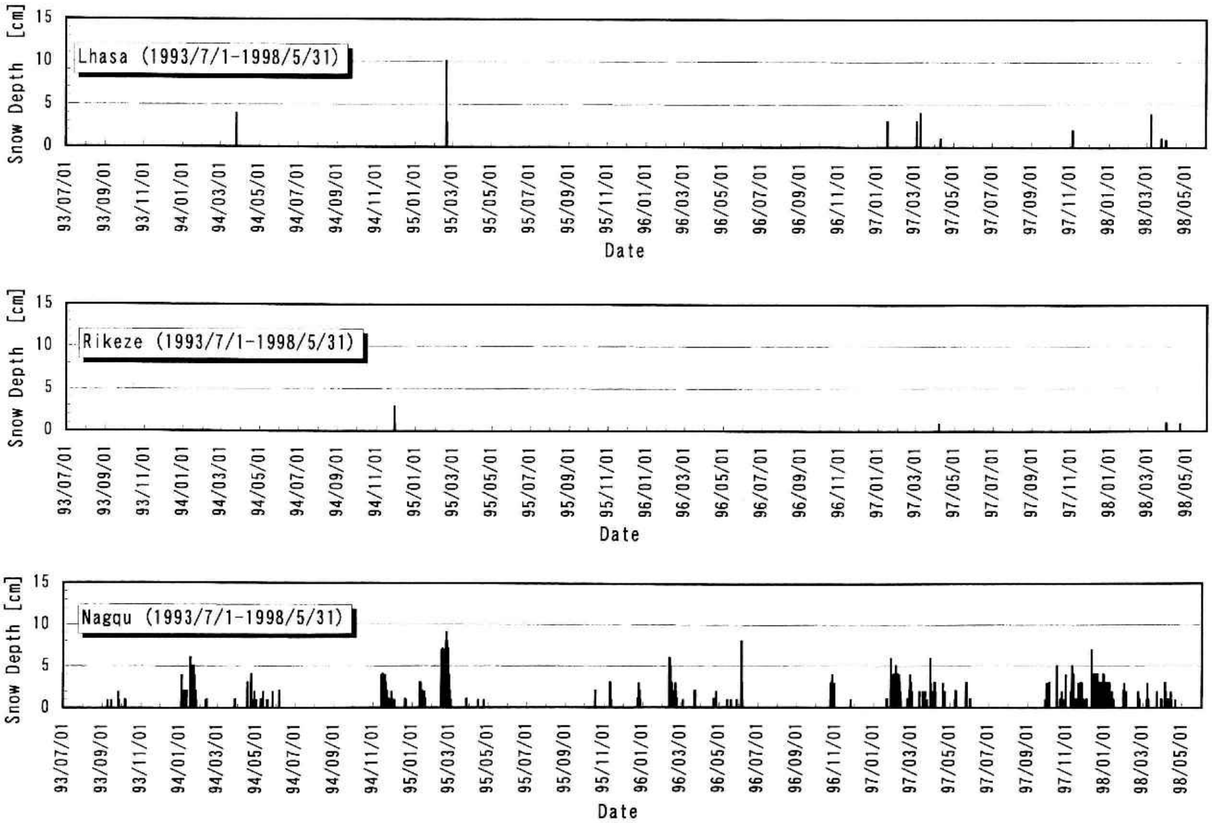


Fig. 9 Time series of snow depth measured routinely at Lhasa, Rikeze and Nagqu.

observed routinely at the meteorological stations. The routine snow depth data in the winter of 98/99 has not yet been obtained. At Nagqu, snow cover did not last the duration of a whole winter and the longest period of snow cover was about one month in the winter of 97/98 when a serious snow disaster occurred in Tibet. The snow depth at Nagqu did not exceed 10 cm across the five winters, which was not ideal for the snow weight observation. Snowfall was infrequent at Lhasa and Rikeze.

Figure 10 shows the routinely measured snow depth and daily precipitation (upper) and the observed daily snow weight after correction (lower) at Nagqu. The open circle in the lower figure indicates snow pressure, which is manually obtained in the routine measurement and is the same as the snow weight. Note that the snow depth and snow pressure data in the winter of 98/99 have not been plotted. The corrected snow weight sometimes has negative values on no snow days, which means that the correction is imperfect. The error in the corrected snow weight is different between the six winters, but should be within ±5 kg/m^2 at the worst. The lower figures show that the snow weight obtained by the two methods are in virtual agreement with each other.

The maximum snow weight across the six winters was observed to be 20 kg/m^2 in the winter of 93/94, which corresponds to 2 cm of water equivalent of snow. The snow weight from December 1997 to January 1998 was about 9 kg/m^2 and it did not decrease rapidly during one month.

4. Discussion

4.1 Temporal variations of air temperature and precipitation

The meteorological conditions during the observation period will be discussed here on the basis of routine data. The monthly mean air temperature at

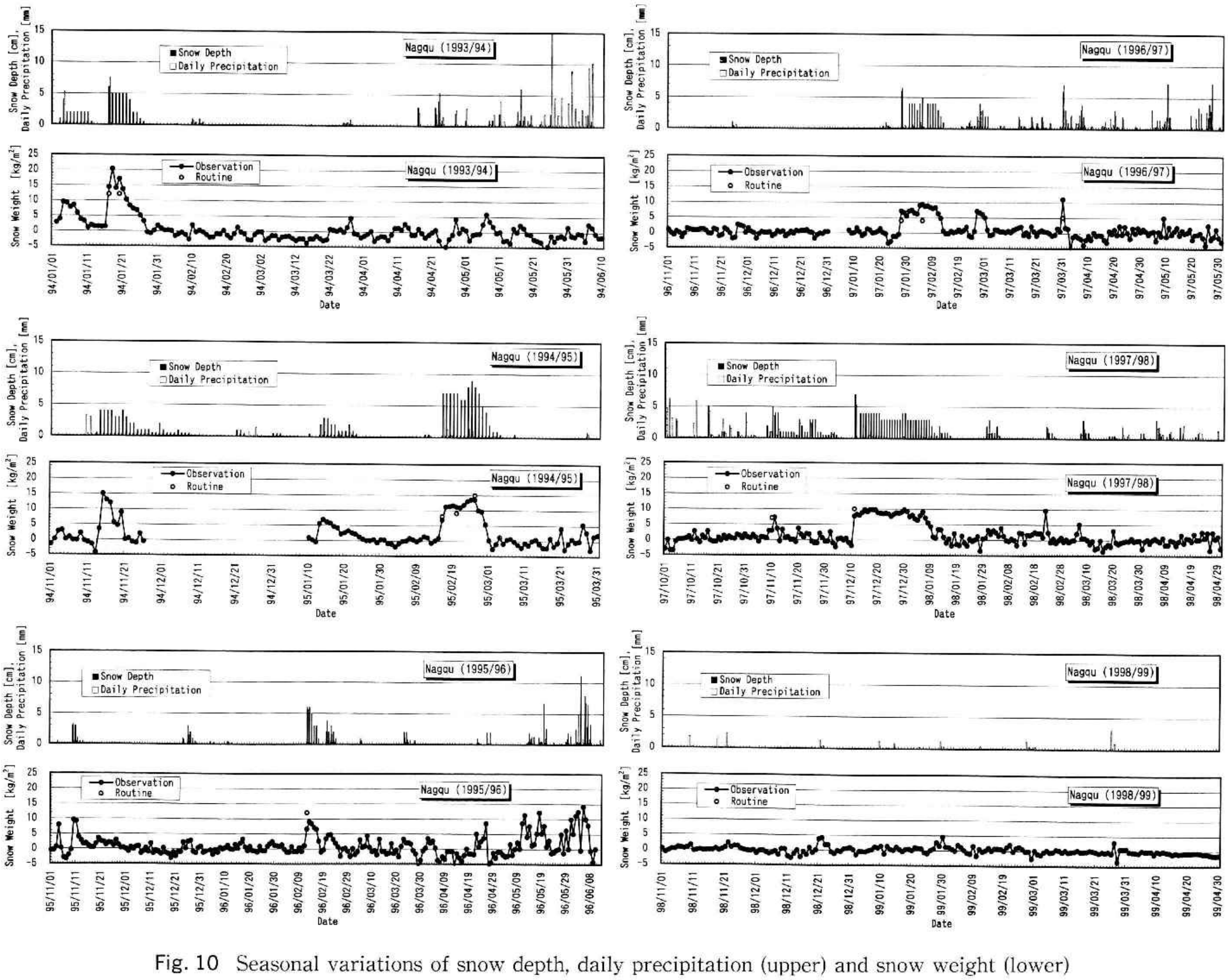


Fig. 10 Seasonal variations of snow depth, daily precipitation (upper) and snow weight (lower) at Nagqu from the winter of 93/94 through the winter of 98/99.

the three sites is plotted in Fig. 11. The average air temperature from 1993 to 1998 was 8.4°C, 6.8°C and −0.9°C, at Lhasa, Rikeze and Nagqu respectively, which decreased with the altitude. The air temperature in the summer was almost constant across the six year period. The mean air temperature in the winter (October—March) shown in Fig. 12, however, varied from year to year.

The monthly precipitation at the three sites is plotted in Fig. 13, showing that the precipitation was confined to the warm season. At Nagqu, winter precipitation was sometimes observed, which remained as snow cover for between several days to about one month. The rainy season, which is one aspect of the monsoon activity over the Tibetan Plateau, began in May or in June and continued until September. Annual precipitation varied year by year.

The precipitation from June through September has a negative correlation to that in May (Fig. 14). This relationship is obvious at Rikeze and Nagqu. The precipitation from June through September is not correlated to either that in March or that in April. Ueno (1998) analyzed the satellite data in 1993 to clarify the rain system over the Tibetan Plateau, and found that the rainy season has two phases: During the first phase from the middle of June to the middle of July, the moisture was brought from outside to the

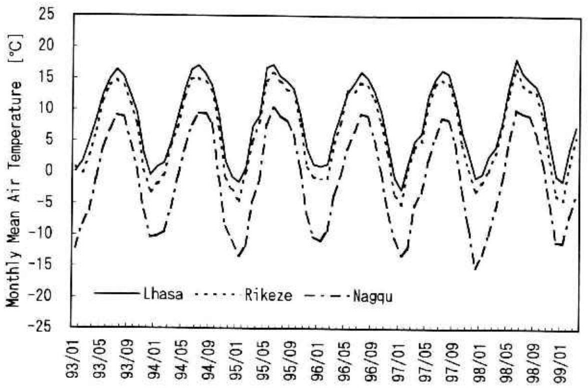


Fig. 11 Monthly mean air temperature at Lhasa, Rikeze and Nagqu from Jan. 1993 to Mar. 1999.

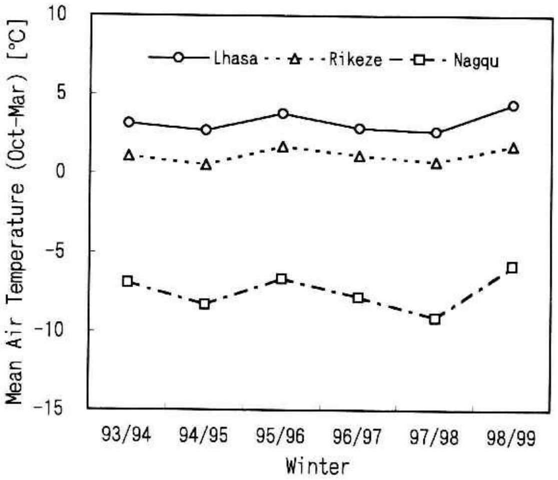


Fig. 12 Mean air temperatures in the winter (Oct.-Mar.) at Lhasa, Rikeze and Nagqu from the winter of 93/94 through the winter of 98/99.

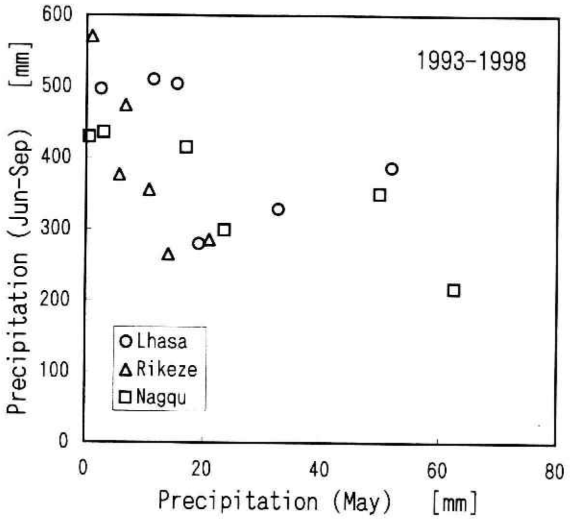


Fig. 14 Precipitation from Jun. through Sep. vs. that in May at Lhasa, Rikeze and Nagqu from 1993 to 1998.

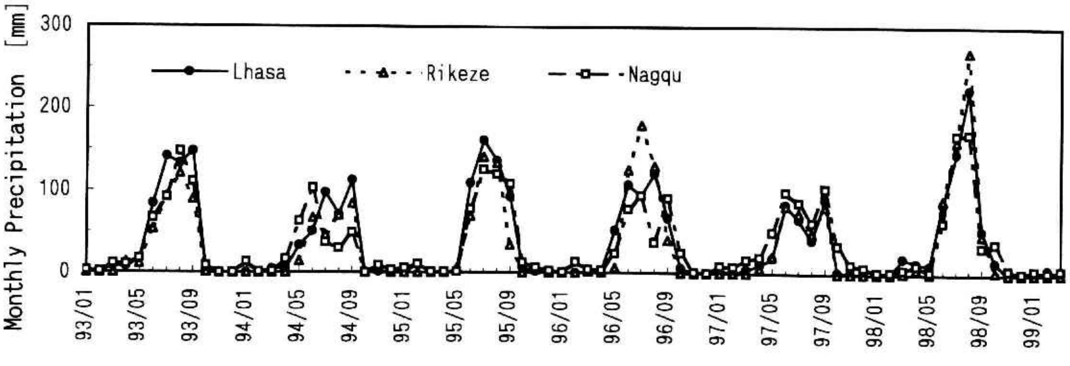


Fig. 13 Monthly precipitation at Lhasa, Rikeze and Nagqu from Jan. 1993 to Mar. 1999.

Plateau by the southwesterly airflow, which is related to the Indian monsoon. During the second phase from the middle of July to the end of August, the moisture was recycled within the Plateau due to the mesoscale circulation system and the precipitations over the Tibetan Plateau and India were not correlated well with each other.

Although the negative correlation of the precipitation from June through September to that in May suggests that the latter suppresses the convection in summer through increases in the soil moisture, the mechanism of the seasonal change of precipitation is a subject of future analysis. It was ascertained from the routine data during the period of 1993-1999 that warm (cold) winters tended to follow wet (dry) summers with much (little) precipitation respectively. However, their statistical significance cannot be discussed due to the short duration of the analysis (6 years).

4.2 Inter-annual variation of snow cover

The cumulative snow depth and days of snow cover at Nagqu are shown in Fig. 15. These were obtained from the routine snow depth data from the winter of 93/94 through the winter of 97/98. Days of snow cover means the number of the days when snow cover existed. Both cumulative snow depth and days of snow cover are correlated with each other. In the winter of 97/98, the cumulative snow depth and days of snow cover registered the maximum values among the five winters and a serious snow disaster occurred in Tibet. It is clear from Figs. 12 and 15 that the winter air temperature was low in the winter with a great deal of snow (94/95, 96/97 and 97/98 winters). If the ground surface is covered with snow, the ground receives less heat than the uncovered ground as the snow reflects solar radiation well. The atmosphere is cooled as a result of this local land-atmosphere heat exchange. On the other hand, the low air temperature in winter is also caused by the cold air advection that is related to large scale phenomena. The reason for the good correlation between the winter air temperature and the cumulative snow depth (days of snow cover) should be clarified by analyzing atmospheric circulation around the Tibetan Plateau and the heat budget of the ground.

The precipitation from June through September at the three sites is plotted in Fig. 16 against the days of snow cover at Nagqu of the preceding winter, showing good correlation between the two sets of data. It was found that there is no correlation between winter precipitation and days of snow cover at Nagqu. In order to discuss the effect of snow cover on the monsoon activity over the Tibetan Plateau, snow cover and precipitation distributions over the Plateau are required, which can be provided by the remote sensing technique. The data obtained in this study at some sites and stations will be useful for the validation of such technique.

4.3 Inter-annual variation of frost depth

As shown in Table 3, the maximum frost depth increased in order of the altitude and varied from year to year at each site. The freezing of the soil is caused by the heat loss from the ground surface during the winter. Sato and Haginoya (1996) analyzed the heat

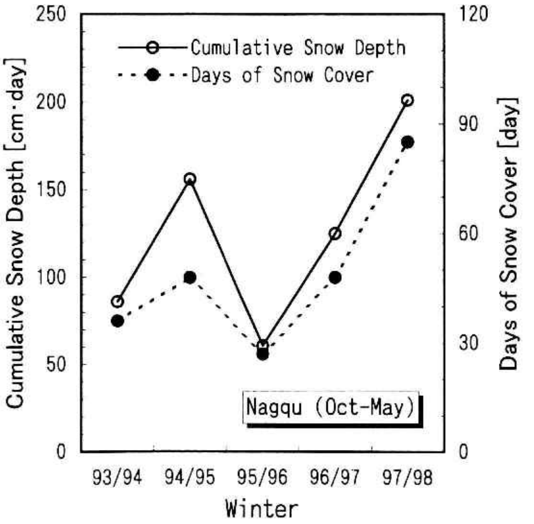


Fig. 15 Cumulative snow depth and days of snow cover at Nagqu from the winter of 93/94 through the winter of 98/99.

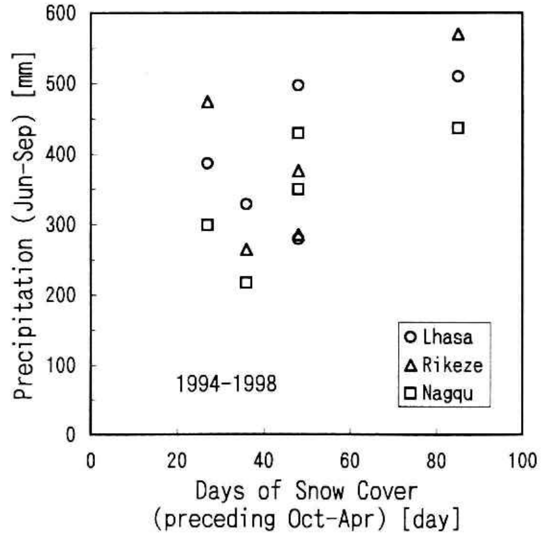


Fig. 16 Precipitation at Lhasa, Rikeze and Nagqu from Jun. through Sep. vs. days of snow cover at Nagqu from the preceding Oct. through Apr.

budget of the ground at Nagqu during the frost penetrating stage and found that the ground loses heat via turbulent heat transport (the sum of sensible and latent heat fluxes). The winter meteorological conditions differed year by year as mentioned before and frost penetration is likely to be affected by these conditions.

According to Kinoshita (1982), the maximum frost depth D (cm) can roughly be expressed by the following equation:

$$D=a\sqrt{I}, \tag{1}$$

where I (°C•day) is the accumulated freezing index defined by

$$I=\Sigma T. \tag{2}$$

Here, T (°C) is the daily mean of air temperature or ground surface temperature, and the summation is only made for negative values of T during the frost penetrating stage. The value of I depends on the meteorological conditions and the coefficient α defined by Eq.(1) represents the efficiency of frost penetration. The value of α depends on the thermal characteristics and moisture levels of the soil. The values of I and α are also listed in Table 3, and differ among the three sites.

Figure 17 shows the relationship between α and the precipitation in the preceding summer (July-September), where positive correlation can be found at Nagqu. The level of soil moisture in the winter is considered to be high after a wet summer with much precipitation. The thermal conductivity and heat capacity of the soil as well as the latent heat release when it freezes depend on the level of soil moisture. The result shown in Fig. 17 suggests that the increase in the soil moisture due to large amount of summer precipitation leads to an increase in heat conduction, which results in a large value for α.

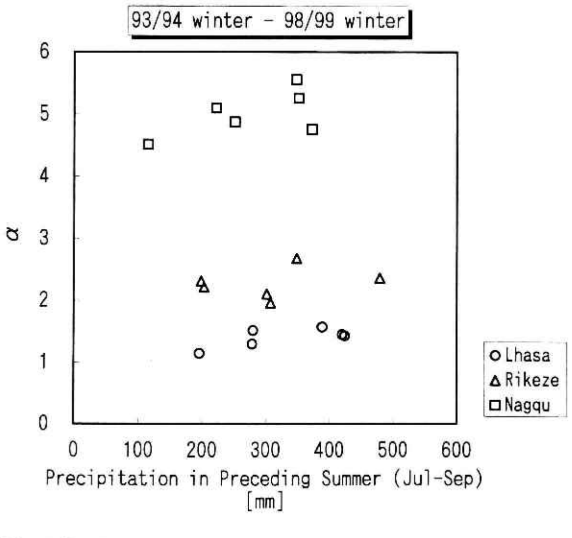


Fig. 17 The coefficient α vs. the precipitation in the preceding summer (Jul.-Sep.) at Lhasa, Rikeze and Nagqu, respectively.

The results of the previous studies on frozen ground are different from the present result. For example, the value of α at Nagqu is much greater than the 2.0-2.5, which were obtained in Hokkaido, Japan, where the soil would be wetter than Nagqu. In addition, the numerical study by Yamazaki *et al.* (1998) showed that the frozen ground does not develop when the soil is wet. Considering that the volumetric soil moisture content at Nagqu was 10-20% for the depth of 0-30cm (Haginoya, 1999, private communication), the dependence of α on the summer precipitation obtained in this study can be a feature of the frozen ground in dry and seasonally frozen ground regions.

4.4 Snow density

Snow density was calculated from the observed snow weight and the routinely measured snow depth. Figure 18 shows the relationship between the snow density and snow depth at Nagqu from the winter of 93/94 through the winter of 97/98, where the data are plotted satisfying the following criterion: a snow cover with the depth of greater than 3 cm continued for more than two days. The snow density ranged from 0.05 to 0.4 g/cm³ and its average was 0.2 g/cm³. Since the snow depth did not exceed 10 cm during the observation period, these snow density values correspond to newly fallen snow and somewhat densificated snow.

5. Concluding remarks

This study has described the features of frozen

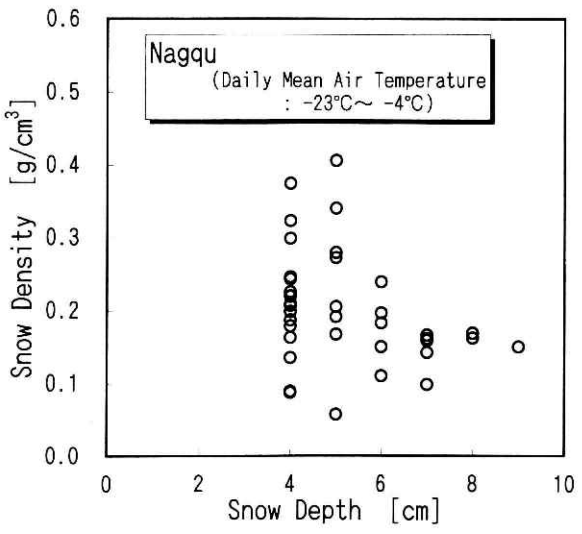


Fig. 18 Snow density vs. snow depth at Nagqu.

ground and snow cover on the basis of the automatic observations of frost depth and snow weight at Lhasa, Rikeze and Nagqu (Nagqu is the highest site) in the eastern part of the Tibetan Plateau from July 1993 through March 1999. The routine meteorological data collected at the same sites was also analyzed for that purpose.

Since the frozen ground was not thick at Lhasa and Rikeze, the results at Nagqu are shown below : In winter, excluding midwinter, the frozen ground sometimes changed within a day, that is, the soil layer near the ground surface sometimes froze during the night and melted during the day. The frost penetration continued until the middle of March when the frost depth attained its maximum value. The maximum frost depth varied according to winter meteorological conditions, and it ranged from 160 to 200 cm across the six winters. The efficiency of frost penetration increased with the precipitation in the preceding summer. These can be said to be the features of the frozen ground in the dry and seasonally frozen ground region.

Two types of frost depth meter were used in this study, which still have some problems. Improvements should be made for the automatic, continuous and accurate observation of frost depth.

Snow cover was hardly observed at Lhasa and Rikeze, and its features at Nagqu are summarized as follows : Long lasting snow cover was not observed. The number of days of snow cover was 27 to 85 days and the snow depth did not exceed 10 cm from the winter of 93/94 through the winter of 97/98. The snow weight was less than 20 kg/m^2 and the snow density ranged 0.05-0.4 g/cm^3 (the average was 0.2 g/cm^3).

The snow weight values observed with the snow weight meter, which was introduced into the Tibetan Plateau for the first time in this study, will be useful for interpreting the satellite images of snow cover. In the future, however, the sensitivity of the snow weight meter should be improved for use in areas of light snow cover and its temperature dependence should be improved.

The relationships between air temperature, precipitation and snow cover were analyzed and the following was revealed : During six years, the winter air temperature varied from year to year and it was negatively correlated to days of snow cover at Nagqu. Warm (cold) winters tended to follow wet (dry) summers with much (little) precipitation respectively. The precipitation from June through September negatively correlated to that in May.

The statistical significance of the above findings should be verified by the analysis of long term data. In order to understand the relationships between the snow cover and frozen ground over the Tibetan Plateau and the Asian monsoon, observation data across a wide area is also required.

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チベット高原において観測された凍土の深さと積雪重量

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要　旨

チベット高原の3ヶ所（ラサ，シガセ，ナチュ）において，1993年7月から1999年3月まで，凍土の深さ（凍結深）と積雪重量の自動観測を行った．観測値と気象官署のルーチンデータを解析し，凍土と積雪の季節変動ならびに年々変動を明らかにした．また，気温，降水量および積雪の間の関係も解析した．

ラサとシガセでは凍土はあまり厚くならなかった．ナチュにおける凍土の特徴は次の通りである：厳冬期を除く冬期間，地表面に近い凍土層は夜間に凍結し，日中に融解するという日変化をした．凍土は10月に出来始め，翌年の3月中旬まで発達を続けた．最大凍結深は，冬期間の気象条件に依存するが，6冬期間で160～200 cmであった．

ラサとシガゼでは，積雪はほとんど観測されなかった．ナチュにおける積雪の特徴は次の通りである：積雪は一冬の間連続して存在することはなかった．93/94年冬期から97/98年冬期の間で，積雪日数は27～85日で，積雪深は10 cmを越えることはなかった．積雪重量は20 kg/m^2 以下で，積雪密度は0.05～0.4 g/cm^3（平均は0.2 g/cm^3）であった．

気温，降水量，積雪の間の関係は次の通りである：解析した6年間において，ナチュでは冬期の気温と積雪日数には負の相関があった．また，夏に雨が多い（少ない）年の次の冬は暖かい（寒い）傾向にあった．6月～9月の降水量は5月の降水量と負の相関があった．しかし，解析期間が6年と短いため，このような関係の統計的有意性についての議論はできなかった．

キーワード：凍土，凍結深，積雪，積雪重量，チベット高原