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Alpine Snow Properties Analysis Based on In-situ Measurements in Binggou Watershed of Qilian Mountain

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Abstract: The alpine snow and its melt can dominate local regional climate and hydrology. Some snow models and quantitative remote sensing of snow require abundant field data of snowpack properties for calibration and validation. In the study, the snow properties were measured using some advanced instruments in Binggou Watershed, and then the temporal and spatial relationships of the properties of snowpack were analyzed. With graduated snow sticks, Snow Fork, hand-loupe with scale and so on, the snow spatial distribution, along with other properties such as snow density, snow liquid water content, snow reflectance, snow surface albedo, snow grain size and temperature was measured during December 2007 and March 2008. In addition, also snow profile properties in conjunction with snow pit work were measured and the Snow Equivalent Density (SED) was calculated. Results of snow depth from graduated snow sticks indicate the spatial distribution of snow depth in alpine is quite heterogeneous. The snow in the shade slope is much deeper than that in the solar slope. The liquid water content derived from Snow Fork is lower than 3%. The measurements of snow spectral reflectance firmly demonstrate that the snow reflectance has a strong dependence on the snow grain size, the snow type (contamination) and surface roughness. Snow surface albedo was measured using a portable albedometer. The results show that the snow surface albedo can vary depending upon the surface liquid water content except for latest snowfalls. Results of the snow pit work exhibit different snow vertical structures: fine snow, old snow, ice, and coarse grain snow. When the snow depth is more than 20 cm, the snow is often a heat preservation layer. The snow equivalent density shows little temporal and spatial variance. After calculation, the SED was 0.16 g/cm^3 as calculated.

Key words: Binggou Watershed; snow survey; snowfall measurement; Snow Fork

1 Introduction

Snow is an important component of the Earth's hydrologic and energy budgets. Mid-latitude alpine snow cover and its subsequent melting can dominate local to regional climate and hydrology in the world's mountainous areas[1]. In northwest of China, alpine snowmelt is the major source of many rivers. Distributed snow models need the following spatially distributed parameters: snow cover area, snow water equivalent, grain size, albedo, temperature, the properties of snow profile, and meteorological conditions[2-3]. In addition, the quantitative remote sensing of snow requires abundant field data of snowpack properties for calibration and validation[4-6]. Measurements of snow properties in the field provide direct determination. However, with the limitation of spatial and temporal extent, risky conditions and observation instruments, there are few field data in mountains, especially in northwest moun-

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tain area, China. Previous researchers have investigated some snow properties in Xinjiang Province[7-8]. The snow data sets are not enough for snow models and remote sensing application.

In this study, a snow survey experiment was designed to measure the snow properties using advanced observation instruments, including Snow Fork, hand-loupe with scale, portable snow albedometer, Analytical Spectral Devices FieldSpec FR field spectroradiometer (ASD-FR) and so on. The intent of the study is to provide comprehensive data sets for snow distribution models and remote sensing application.

The study area is Binggou Watershed (Fig. 1), which is headwater of Heihe River. The watershed is located in Qilian Mountains, Qinghai Province of China. It has an area of 30.5 km^2 with an elevation ranging from 3431 m to 4400 m. The mean annual precipitation is 774 mm[9]. In the watershed, we selected five representative square sub-regions located on different altitude and topography to measure the snow properties. The sub-regions named A, B, C, D, E with the domain of 90 m × 90 m, 60 m × 60 m, 60 m × 60 m, 90 m × 90 m, 90 m × 90 m, respectively. In addition, five groups of graduated snow sticks were also beforehand arranged for measuring the distribution of snow depth. Two automatic weather stations, one located in the mountaintop of watershed and the other in the mountainside, will monitor ambient conditions and provide forcing data sets snow models. Fig. 1 shows the details. The five square sub-regions were divided into 30 m × 30 m grid. With at least 3 measurements of random points per grid cell, we obtain the data of snow properties. Based on a 60 m × 60 m area, details of the sample plan are shown in Fig. 2. The snow survey experiment was first carried out in December, 2007, and later in March, 2008. It will focus on two characteristic seasons: 1) mid-winter, when frozen conditions and dry-cold snow covers prevail; 2) early spring, when transitional (frozen to thawed) conditions and wet snow covers are prevalent.

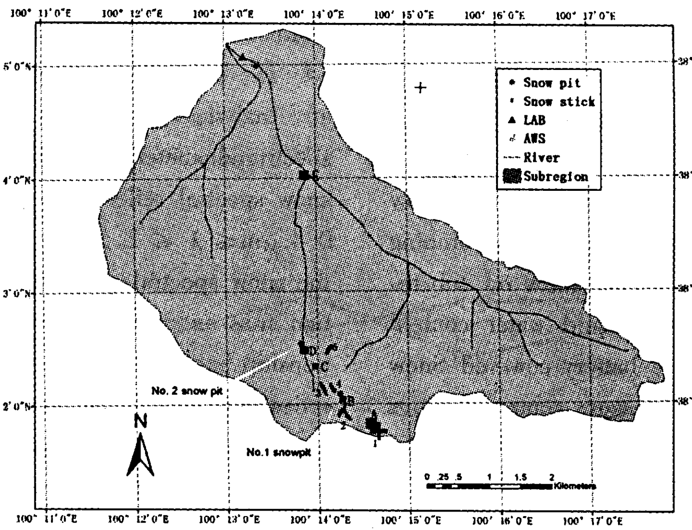


Fig. 1 The study area of Binggou watershed and details of watershed, including five sub-regions, five groups of graduated snow sticks, snow pits, two automatic weather stations and the Binggou lab

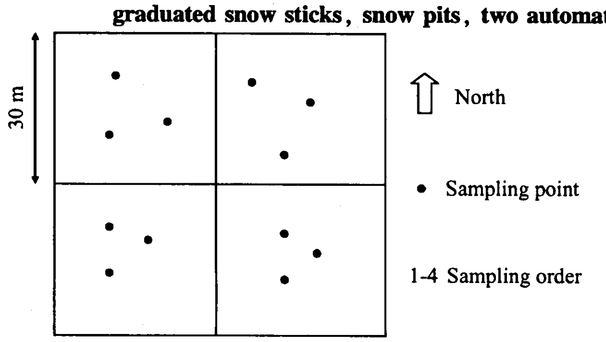


Fig. 2 The sampling method in square sub-regions (60 m × 60 m)

2 Data source and the observing methods

The collection of snow properties measurements is a major and critical component in the snow survey experiment. In the watershed, the measurements are mainly focused on quantifying the spatial mean, variance, and distribution of snow depth by the graduated snow sticks. At the sub-regions, the measurements are focused on measuring the snow properties.

2.1 Spatial distribution of snow depth

The spatial and temporal distribution of snow depth plays an important role, not only in estimating the snow water equivalent accurately, but also in snow explicit models. In the experiment, we arranged five groups of graduated snow sticks, which were set in advance by different topography and solar radiation. Tab. 1 shows the details of graduated snow sticks, including number, slope, topography, and so on. Each graduated snow stick of per group was separately set at interval of 20 m. The length of snow sticks, which were colored with red and white with 0.2 m interval of each part, is 2 m. Close range measurements of the snow sticks provide direct determination, but they are inconvenient at limits of weather and topography under risky conditions. Then, a two-eye telescope is utilized to measure the snow depth when the graduated snow sticks are located in inapproachable place. The measurements of graduated snow sticks were carried out at 10 from March 2^{nd}, 2008 to April 6^{th}, 2008. During the period, we measured the snow depth of 8 days.

Tab. 1 The details of graduated snow sticks

Group	Number	Average slope/(°)	Average altitude/m	Topography
1	17	3.7	4140	Flat mountaintop
2	12	19.5	4071	Shade slope
3	9	27.8	3980	Semi-solar slope (sun in a.m.)
4	6	26.3	4011	Semi-shade slope (sun in p.m.)
5	7	26.2	4004	Solar slope

2.2 Snow properties

In all sub-regions, the experiment has been focused on measuring the snow depth, snow density, snow liquid water content, the snow grain size, the snow surface temperature, snow spectral reflectance and snow albedo.

Besides the graduated snow sticks, the snow depth was measured to the nearest 0.01 m by probing vertically into the snow pack using rules on sub-regions. Snow density and snow liquid water content were measured with a portable battery-powered Snow Fork, which was designed to measure snow properties in the field by Finland Helsinki University. It can be operated in the cold environment and possess the capacity of automatic observation at 15-minute intervals. The frequency, bandwidth and attenuation were directly measured, then the liquid water content (liquid water content by volume and weight), density, and permittivity can be calculated automatically. The error of instrument is very small except for very high wetness values.

The snow grain size was measured by a handheld loupe with scale and the shape of snow samples was also recorded. The method is time-consuming, so we only measured the long-axis diameter of snow grain. In each of the sample points, three measurements of the grain size are taken for an average. The snow surface layer temperature was measured by a thermal infrared thermometer. The average temperature will be calculated. The snow spectral reflectance was measured with an Analytical Spectral Devices FieldSpec FR field spectroradiometer (ASD-FR) that rapidly measures the snow spectral reflectance across the wavelength range $0.4\ \mu m \leqslant \lambda \leqslant 2.5\ \mu m$. In the study, we measured the snow spectral reflectance at the different observation sites and snowpack conditions to assess the relationship between the snow spectral and the snow properties. In addition, with an Automatic Spectro-Goniometer (ASG), the spectral Bidirectional Reflectance Factor (BRF) of snow was measured. The ASG has a two-link metal pole controller coupled with a field spectroradiometer. The snow albedo was measured by a portable albedometers. It is composed of two Kipp & Zone CMP 3 pyranometers that are mounted opposite to each other. A rod was screwed in one of the housings for fixating the mounted instruments to a mast. Each sensor has a separate cable that links a pocket ammeter. The magnitude of the voltage of ammeter is directly measured. Surface albedo can be defined as the ratio of upwelling radiation to the downwelling irradiance to that surface. Then, the snow albedo can be calculated. Meanwhile, the location of observation and the time have been recorded.

2.3 Snow profile

Measurements of the vertical profile of several snow properties such as snow depth, snow grain size, snow shape, snow temperature, snow liquid water content and snow density were collected in the study. Snow pit measurements are taken from the vertical wall of each pit. Significant layer boundaries are observed. From each significant layer, snow depth, snow grain size and snow shape was measured using a handheld loupe with scale. Snow liquid water content, density and temperature were measured at 10-cm intervals. The snow deeper layer temperature was measured with a needle-type thermometer. In conjoined with snow pit work, the snow/soil interface temperature was measured using a thermal infrared thermometer. Some snow pits are located outside the sub-regions. Then, the locations were recorded by a handheld Global Positioning System (GPS).

3 Analisis of the snow data sets

The snow survey experiment is designed to get the snow data sets of the alpine regions. The snow data sets can be applied in quantitative remote sensing and snow explicit models. In this section, we mainly introduce the analysis of snow depth distribution and snow properties.

3.1 The spatial distribution of alpine snow

In the experiment, the 8 days measurements of graduated snow sticks were collected during March 2nd and April 6th, 2008. Then, the average snow depth of each group was calculated. As shown in Tab. 1, the graduated snow sticks were set basing on different topography. Fig. 3 shows the daily average snow depth of five groups of snow sticks. During the observation period, the snow average depth is 15.9 cm, 36.6 cm, 16.8 cm, 43.4 cm, and 1.3 cm respectively from snow sticks of No. 1 to No. 5. The results show that the alpine snow is heterogenous. The snow of the solar slope is the shallowest. The snow of the semi-shade slope (sun in p. m.) is the deepest. During the same time, the snow depth of the solar slope is lower than 3 cm, whereas the snow in other topography is more than 30 cm. There are many factors contributed to the distribution of alpine snow, including the topography, roughness, redistribution of blowing snow, and the radiant energy.

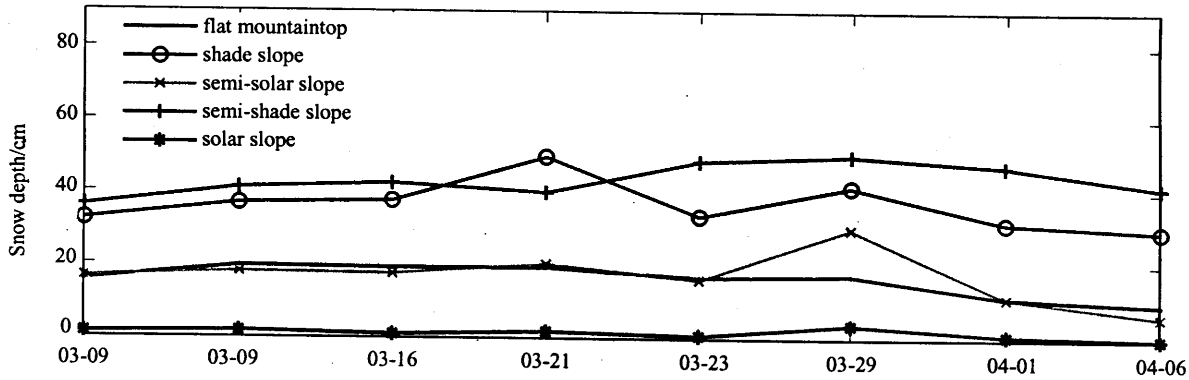


Fig. 3 The average snow depth of graduated snow sticks during early spring of 2008

3.2 The analysis of snow physical properties

The alpine snow is of complicated layer structure and characteristic. In the experiment, two snow pits in the B and D sub-regions respectively were measured basing on five snow types (fine snow, granular snow, coarse snow, hoar crystal, and ice) on April 5th, 2008. The definitions of the snow type are based on the snow grain size and shape. Tab. 2 shows the results of the snow pit measurements in the B sub-region. The results indicate that the hoar crystal is well-developed in Binggou Watershed. The temperature difference of the snow layer is mainly contributed to the production of snow hoar crystal. The results also indicate that the snow layer temperature reduces with the increase of snow depth. However, when the snow depth is more than 20 cm, the temperature gradually increases. Then, the snow is often a heat preservation layer.

Tab. 2 The snow pit measurements in the B sub-region on April 5th, 2008

Snow type	Snow depth/cm	Temperature /℃	Snow density /(g · cm^{-3})	Snow grain radius/μm	Snow liquid water content/%	Notes
Granular snow	1.5	-0.9	0.20	350	2.61	
Fine snow	2.5	-4.4	0.17	150	0.46	
Ice	2.5	non	non	non	non	The surface is mainly covered
Hoar crystal	2.5	-8.0	0.14	500	0.33	with complete snow.
Coarse snow	5	-8.5	0.28	800	1.31	The sky is clear.
Ice	1.5	non	non	non	non	The depth of snow pit is 64 cm
Granular snow	10.5	-7.9	0.27	750	1.17	The temperature of snow
Hoar crystal	13	-5.4	0.12	750	0.90	surface is -5.5 ℃
Coarse snow	2	-4.5	0.16	1500	0.47	
Hoar crystal	13	-3.6	0.12	2500	0.78	

For evaluating snow water equivalent, we measured the snow density profile in conjunction with snow pit work at 10-cm intervals. Then, the snow equivalent density (*SED*) is defined, which is given by the following equations,

$$SWE = \sum_{i=1}^{n} (\rho_i d_i) \quad (1)$$

$$SWD = \frac{SWE}{D} \quad (2)$$

where *SWE* is the Snow Water Equivalent of snow pits, n is snow layer number, which is classified at 10-cm intervals, ρ_i is the snow density of No. i layer, D is the depth of the snow pit, and *SED* is the Snow Equivalent Density of the snow pit. By the Eq. (1) and (2), the *SED* was calculated. Tab. 3 shows the results during different observation periods. The results indicate that the snow equivalent density is little different at different locations and timescales. As calculated, the overall *SED* is about 0.16 g/cm^3.

Tab. 3 The snow equivalent density (*SED*) of A, B, C, D sub-regions during the observation periods

Sub-region	*SED**/(g · cm^{-3})	*SED***/(g · cm^{-3})
A	0.165	0.168
B	0.142	0.157
C	0.164	0.158
D	NAN	0.156
Average	0.157	0.160
Overall average	0.158	

* In December, 2007; ** In March, 2008

The 257 snow samples in different layers were collected. The analysis exhibit the snow liquid water content is larger at the near-surface layer and somewhat lower at the deep layer. In general, the surface wetness is lower than 3%, while that at the deep layer less than 1%. Fig. 4 shows the snow liquid water content of all snow samples. The general classification scheme of the International Association of Scientific Hydrology (IAHS) will be used[10]. The percentage of liquid water by volume is classified as dry (0%), moist (<3%), wet (3% ~ 8%), very wet (8% ~ 15%), and slush (>15%). The snow of the study area belongs to moist.

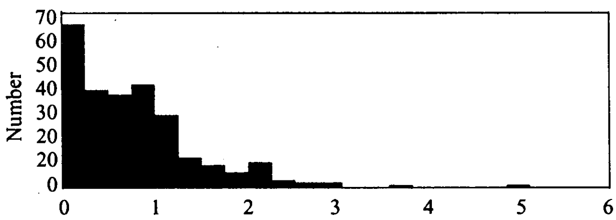
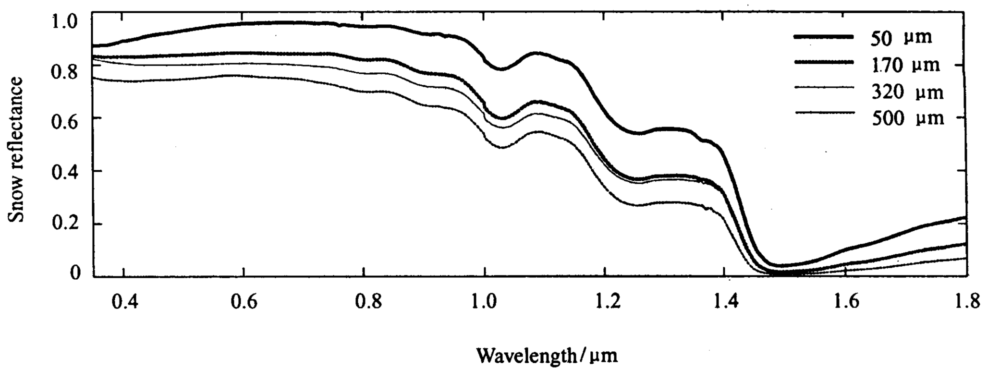


Fig. 4 The histogram of snow liquid water content derived from Snow Fork.

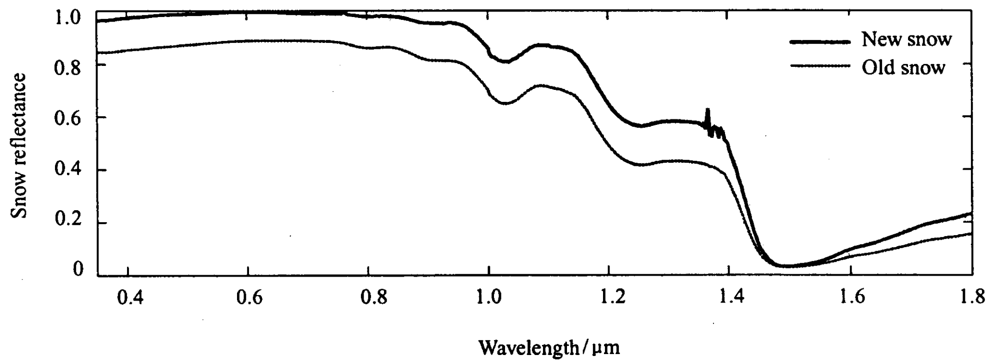
3.3 The analysis of snow optical properties

The snow spectral reflectance is measured in A sub-region using ASD-FR. Fig. 5 shows three different snow reflectance features of the band around λ = 350 ~ 1800 nm measured in this experiment: 1) snow reflectance of different snow grain size; 2) snow reflectance of different snow contamination; 3) snow reflectance of different snow surface roughness. The dependence of the snow reflectance on the snow grain size, contamination and surface roughness observed in the study is quite consistent with the results by Male[11]. The results indicate in the visible and near-infrared part of the spectrum, the snow reflectance decreases as the grain size increases. The new snow is larger reflectance than old snow. When snow grain size and contamination are the same, the snow reflectance of the flat surface is larger than rugged surface. In addition, we measured a wide range of spectra for other representative ground objects including rock, soil, ice, shallow snow and vegetation in order to mapping subpixel snow-covered area.

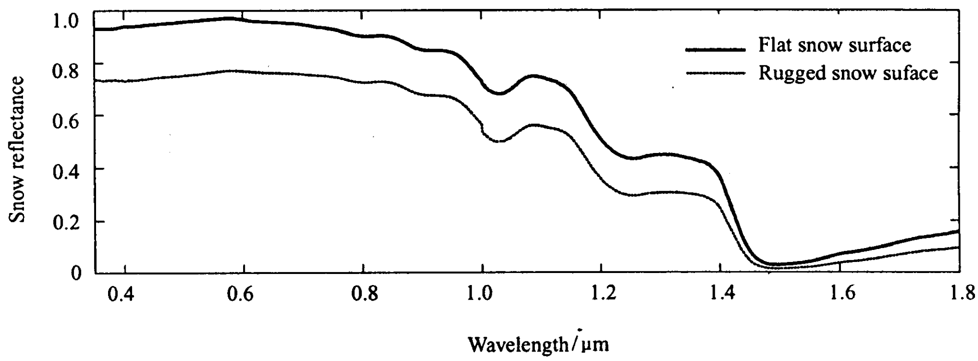
With a portable albedometer, four days snow albedo measurements were obtained at A sub-region. The height of albedometer is about 1.5 m and the measurements are collected at 5-minute intervals. The sky is clear during observation periods. The results of snow albedo are shown in Fig. 6. The albedo gradually decreases from the morning to the noon due to the increases of snow surface liquid water content. Because of snow melt and contamination, the albedo on March 19th is somewhat lower than that of March 17th and the albedo on March 22th is lower than that of March 24th. There is a new snowfall between March 19th and March 22th. The abledo increases rapidly from 60% to 80%.



(a) The relationship between snow reflectance and grain size



(b) The relationship between snow reflectance and contamination



(c) The relationship between snow reflectance and roughness of snow surface

Fig. 5 The snow reflectance measurements using ASD-FR

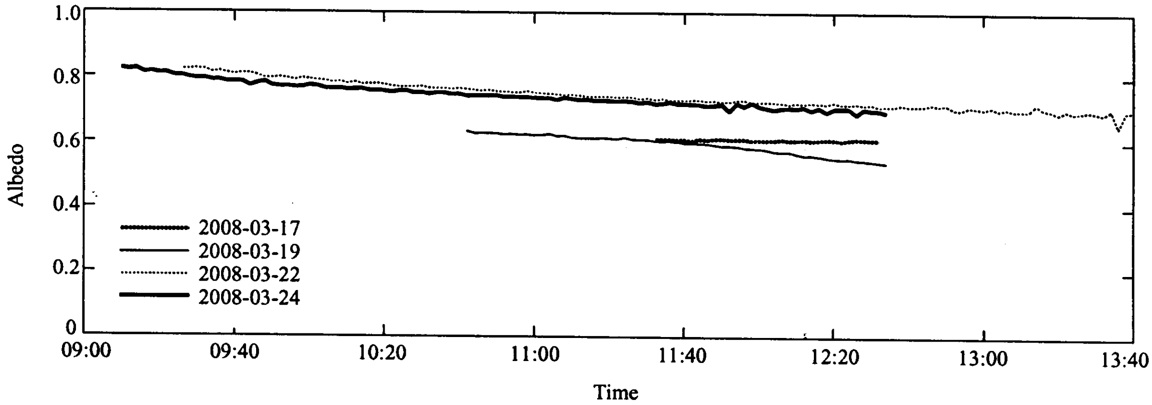


Fig. 6 The daily albedo variation derived from a portable albedometer

4 Conclusions

One of the objectives of the snow survey experiment is to investigate the alpine snow properties, and another important objective is to provide high-quality data sets to remote sensing algorithms and snow explicit models. In the snow survey experiment, many snow properties were measured and analyzed with advanced methods. The experiment improved our understanding of the alpine snow.

Our results clearly indicate that snow depth is spatially heterogeneous, reflecting the influences of rugged topography on precipitation, wind redistribution of snow, and surface energy fluxes during the accumulation season in rugged mountain regions. The snow in Binggou watershed is seasonal. The hoar crystal is well-developed in Binggou watershed due to the lager temperature difference of snow profile. The snow liquid water is lower than 3% during observation periods, and it is dry-cold snow.

The accuracy of the experiment methods was evaluated. The snow equivalent density was calculated to improve SWE model. We also measured the snow temperature profile, soil/snow interface temperature, the snow grain size, snow spectral reflectance, and snow albedo. The snow measurements can be used to evaluate and improve retrieval algorithms for space-borne microwave sensors and visible sensors.

References:

[1] Dozier J, Painter T H. Multispectral and hyperspectral remote sensing of alpine snow properties[J]. Annu Rev Earth Planet, 2001, 32:465 - 494.

[2] Cline D W, Bales R C, Dozier J. Estimating the spatial distribution of snow in mountain basins using remote sensing and energy alance modeling[J]. Water Resour Res, 1998, 34:1275 - 1285.

[3] Luce C H, Tarboton D G, Cooley K R. The influence of the spatial distribution of snow on basin-averaged snowmelt[J]. Hydrol Process, 1998, 12:1671 - 83.

[4] Nolin A W, Dozier J. A hyperspectral method for remotely sensing the grain size of snow[J]. Remote Sensing of Environment, 2000, 74(2):207 - 216.

[5] Klein A G, Barnett A C. Validation of daily MODIS snow cover maps of the Upper Rio Grande River Basin for the 2000 ~ 2001 snow year[J]. Remote Sensing of Environment, 2003, 86: 162 - 176.

[6] Stroeve J, Box J, Haran T. Evaluation of the MODIS (MOD10A) Daily snow albedo product over the Greenland ice sheet[J]. Remote Sensing of Environment, 2006, 105: 155 - 171.

[7] Daqing Y, Chunzu W, Yinsheng Z. Distribution of seasonal snowcover and variation of snow density on the headwaters of Urumqi River Basin[J]. Geographical Research, 1992, 11(4): 86 - 96.

[8] Wenshou W, Dahe Q, Mingzhe L. Properties and structure of the seasonal snow cover in the northwest regions of China[J]. Arid Land Geography, 2001, 24(4):310 - 314.

[9] Zhenniang Y, Zhihuai Y, Xuecheng Z. Runoff and its generation model of cold region in Binggou Basin of Qilian Mountain [R]. Memoirs of Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, 1992, 7:91 - 100.

[10] Colbeck S C, Akitaya E, Armstrong R, et al. The international classification for seasonal snow on the ground[C]//Wallingford, Oxfordshire' International Association of Hydrological Sciences, International Commission on Snow and Ice. 1990.

[11] Male D H, Granger R J. The seasonal snowcover[M]// Colbeck S. Dynamics of Snow and Ice Masses. Toronto: Academic Press, 1980:305 - 395.