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Jian Wang
Hongxing Li
Xiaohua Hao
Xiaodong Huang
Jinliang Hou
Tao Che
Liyun Dai
Tiangang Liang
Chunlin Huang
Hongyi Li
Zhiguang Tang
Zengyan Wang

SPIE.

REVIEW

Remote sensing for snow hydrology in China: challenges and perspectives

Jian Wang,[a,*] Hongxing Li,[a,b] Xiaohua Hao,[a] Xiaodong Huang,[c] Jinliang Hou,[a] Tao Che,[a] Liyun Dai,[a] Tiangang Liang,[c] Chunlin Huang,[a] Hongyi Li,[a] Zhiguang Tang,[a] and Zengyan Wang[a]

[a]Chinese Academy of Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Donggang West Road 322, Lanzhou 730000, China

[b]University of Chinese Academy of Science, No. 19A Yuquan Road, Beijing 100049, China

[c]Lanzhou University, College of Pastoral Agriculture Science and Technology, State Key Laboratory of Grassland Agro-ecosystems, Tianshui Road 222, Lanzhou 730020, China

Abstract. Snow is one of the most important components of the cryosphere. Remote sensing of snow focuses on the retrieval of snow parameters and monitoring of variations in snow using satellite data. These parameters are key inputs for hydrological and atmospheric models. Over the past 30 years, the field of snow remote sensing has grown dramatically in China. The 30-year achievements of research in different aspects of snow remote sensing in China, especially in (1) methods of retrieving snow cover, snow depth/snow water equivalent, and grain size and (2) applications to snowmelt runoff modeling, snow response on climate change, and remote sensing monitoring of snow-caused disasters are reviewed/summarized. The importance of the first remote sensing experiment on snow parameters at the upper reaches of the Heihe River Basin, in 2008, is also highlighted. A series of experiments, referred to as the Cooperative Observation Series for Snow (COSS), focus on some key topics on remote sensing of snow. COSS has been implemented for 3 years and will continue in different snow pattern regions of China. The snow assimilation system has been established in some regions using advanced ensemble Kalman filters. Finally, an outlook for the future of remote sensing of snow in China is given. [DOI: 10.1117/1.JRS.8.084687]

Keywords: remote sensing of snow; snow hydrology; snow disaster.

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1 Introduction

Snow is an important, though highly variable, earth surface cover.[1] In terms of spatial extent, snow cover is the second largest component of the cryosphere after seasonally frozen ground (~65 million km^2), with a mean maximum areal extent of 47 million km^2. Approximately 98% of snow cover is located in the Northern Hemisphere, where temporal variability is dominated by the seasonal cycle.[2] Because of its high albedo, snow is a significant factor in determining the radiation balance, which has implications for global climate studies.[3] Mid-latitude alpine snow cover and its subsequent melt can dominate the local and/or regional climate and hydrological process; thus, there has been an increased focus on snow cover in the world's mountainous regions. Moreover, the extent and dynamics of snow and ice cover affect many hydrological, physical, chemical, and biological processes.[4] Accurate monitoring of snow cover extent, snow water equivalent (SWE), and other properties of snow is pivotal in research areas in the fields of hydrology, climate change, and human-environment interaction. Satellites are well suited to the measurement of snow parameters, as they provide multiplatform, multispectrum, and multiscale observations. Snow is a unique ecosystem with its own annual and interannual variations.

*Address all correspondence to: Jian Wang, E-mail: wjian@lzb.ac.cn

It contributes to resources and activities, such as water supply, hydropower navigation, aquaproducts, recreation, flood mitigation, water storage, soil conservation, pollutant purification, biodiversity, tourism, and entertainment.

In China, snow is an important fresh water resource; annual snowfall recharge is more than six times the amount of glacial meltwater and is approximately equal to 43% of the annual dynamic reserves of groundwater, as well as 1.6 times the storage of freshwater lakes.[5] In the mid-latitude arid and semiarid mountain regions of China, more than 75% of river water is from snowmelt runoff.[6] Snow cover over the Tibetan Plateau is a vital water source in western China; the headwaters of many large rivers (e.g., Yangtze River, Yellow River) originate there. Additionally, industry and agriculture are influenced and restricted by snow cover. Grasslands and pastoral areas have suffered from heavy snow disasters. A strong correlation has been discovered between snow over the Tibetan Plateau and floods in the south and east of China. For instance, flooding of the Yangtze River in 1998 was linked to heavy snow cover over the Tibetan Plateau.[7] In recent years, there has been a high frequency of snow disasters in the southern parts of China, indicating the importance of monitoring snow distribution and variations using satellite remote sensing data.

2 Development of Snow Remote Sensing in China

Since the establishment of snow and glacier expeditions in 1958, supported by the Chinese Academy of Sciences (CAS), great progress has been made in cryosphere research for China. In 1978, under the advocacy of academician Yafeng Shi, the Lanzhou Institute of Glaciology and Cryopedology in the CAS organized a glacier remote sensing group. In 1983, it was reorganized as the Laboratory of Remote Sensing Applications in Cold Regions and is currently China's leader in snow remote sensing research. The forecasting of snowmelt runoff is the primary research focus of snow remote sensing in China due to the associated economic impacts. For example, researchers at the Lanzhou Institute of Glaciology and Cryopedology used data from a National Oceanic and Atmospheric Administration (NOAA)-5 high resolution radiometer to study the snow cover and snowmelt runoff in the northeast and north of China.[8] Further studies occurred in the Heihe River Basin in the Qilian Mountains and in the upper stream of the Longyang Gorge in the Yellow River Basin, leading to a positive economic outcome.[9–12] Recent research has focused on the relationship between climate change and mountainous snow cover and snowmelt runoff.[13] In the late 1990s, under cooperation between the Chinese Meteorological Administration and the Department of Transportation, several statistical models were developed based on data from remote sensing studies of snow disasters in the pastoral areas of China.[14] Recently, basic remote sensing research, especially the electromagnetic properties of glaciers and snow, has improved due to the use of spectral measurements and the selection of optimal satellite spectral wavebands from the Earth Resources Technology Satellite of China.[15] Researchers at Fudan University investigated microwave scattering and thermal radiation of sea ice and snow cover using vector radiative transfer theory,[16] which provides a solid basis for understanding passive microwave remote sensing of the cryosphere.

Since the beginning of the CAS Knowledge Innovation Project in 1999, the field of snow remote sensing has rapidly developed. Quantitative remote sensing, cold region hydrological remote sensing, and ground synchronous experimental observations are new research areas within China. In 2008, we carried out a remote sensing and ground synchronous observation experiment in the Heihe River Basin. Results obtained from snow parameter measurements enhance the understanding of snow hydrological processes; this has a profound impact on snow remote sensing in China.[17] In 2010, a Cooperative Observation Series for Snow (COSS) was designed and implemented in order to study specific research questions. To date, COSS has conducted a series of experiments in different snow pattern regions in China. In recent years, snow cover and its distribution, obtained using satellite data, have been studied extensively. This includes algorithm improvement and validation and product development supported by projects such as the basic research projects by MOST (Ministry of Science and Technology of the People's Republic of China). These projects analyzed snow parameters at different scales in order to understand the impacts of climatic change and global warming. Aiming to summarize and integrate research results of snow remote sensing in China, the first conference of snow remote sensing convened in Lanzhou City on August 1 to 2, 2013. Five topics were discussed: snow measurement and observation, radiation transmission theory and models on snow, optical remote sensing on snow, microwave remote sensing on snow, and applications of snow remote sensing. A total of 68 scientists from 20 institutes and universities exchanged the latest research results and conclusions at this conference. This meeting, named "the snowman exchange," will be held every 2 years in China.

3 Retrieving Snow Parameters from Remote Sensing Imagery

3.1 *Snow Cover Area*

Initially, snow was successfully mapped by visual interpretation using ESSA-3 satellite data.[18] These maps have been continually improved with the addition of new satellite data, such as the Landsat Multispectral Scanning Subsystem, the Landsat Thematic Mapper (TM), the NOAA Advanced Very High Resolution Radiometer (AVHRR), and the Moderate-Resolution Imaging Spectrometer (MODIS).[19–22] Some operational regional or global snow cover binary products have also been issued and can be readily acquired.[23,24] In China, there have been many studies of snow cover mapping since the 1980s. Based on field measurements of snow and ice reflectance values, Zeng et al.[25] and Cao et al.[26] searched the optimal bands for snow cover retrieval. Ma et al.[27] utilized supervised classification (SC) of NOAA-AVHRR data to map the snow cover area in Northern Xinjiang, China. Because these methods are not automated, they can only be used for snow mapping in local regions. Using TM, AVHRR, and MODIS images, Wang[28,29] assessed the accuracy of three methods: training sites' SC, digital numbers' statistics, and the Normalized Difference Snow Index (NDSI)—they found the NDSI method to be more accurate. With the development of sensor techniques, various snow cover data have been improved. Xiao et al.[30,31] developed a snow cover product using SPOT-VEGETATION data. Yan[32] developed a complex index method to map snow cover and mask cloud cover using NOAA-16 data. In addition, Li et al.[33] produced a daily snow product by combining one day's worth of multitemporal images at a spatial resolution of ∼5 km, based on FY-2 satellite data. In general, although there are many snow cover products developed using different methods and remote sensors, MODIS snow cover products, which are produced by the NDSI method and derived from the NASA National Snow and Ice Data Center (NSIDC), are more accurate and are widely used in China.[34]

The NDSI threshold, used for retrieving MODIS snow cover products, obtained from MODIS global snow cover products, was initially developed and validated in the United States, Canada, and Russia. Hao and Wang[35] showed that the MODIS snow cover product underestimated snow cover in the Qilian Mountains and that the regional NDSI threshold is much less than 0.4. In addition, a common challenge is how to exclude the cloud pixels in snow cover products. To address this, a series of blending algorithms which provide daily no-cloud snow cover from MODIS data have been developed and include the following: daily Terra-Aqua/MODIS image combination,[36–40] temporal deduction,[41] the snow-line method (SnowL),[42] and multisensor combinations.[43] Hao et al.[44] developed a blending algorithm which can provide daily no-cloud snow cover from MODIS data by adjusting the NDSI threshold value and combining MODIS and AMSR-E data. This method was used to produce 3-years' (2008 to 2010) worth of daily no-cloud snow cover products of the Qinghai–Tibet Plateau. Figure 1 shows the workflow of the improved MODIS cloud removal algorithm applied to the Qinghai–Tibet Plateau on January 25, 2008. In the study, there are three steps needed to produce the snow cover products. The output from each step is the input for the next step. Moreover, by combining the previous cloud removal algorithms, Huang et al.[45] generated a new daily cloud-free snow cover product using MODIS daily snow cover products (MOD10A1, MYD10A1), an AMSR-E daily SWE product, and a digital elevation model. This method is expected to play an important role in improving the accuracy of snow cover monitoring. Considering the inherent deficiency of MODIS data—that patchy snow or snow depth of below 3 cm is often missed—the improved snow products show agreement up to 91.7% with an overall accuracy of 91.9%. Figure 2 shows

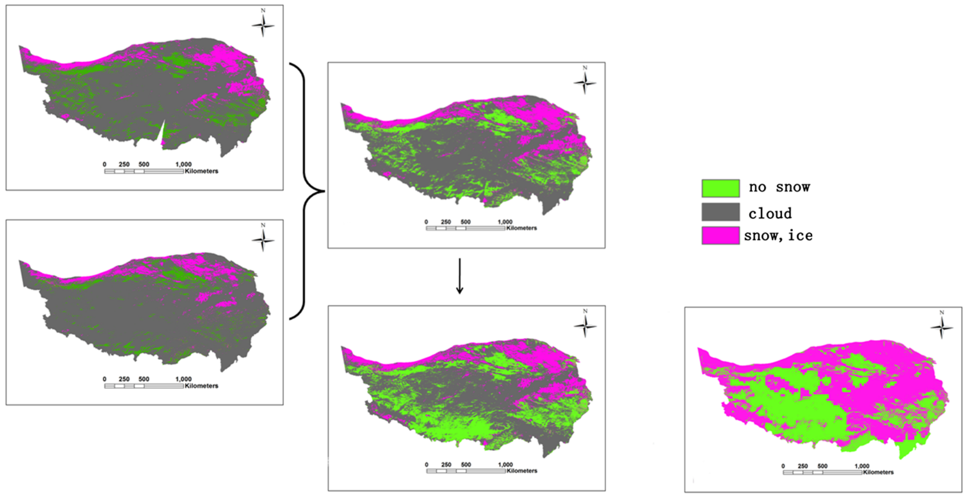

Fig. 1 The workflow of the improved MODIS cloud removal algorithm in the Qinghai–Tibet Plateau on January 25, 2008. First, the image fusion of MODIS Terra and Aqua snow cover products which have been improved by adjusting of NDSI. The second step deduces the cloud-covered pixel based on the one day forward and one day backward information of same pixels. Finally, blending MODIS snow cover and improved AMSR-E Snow depth data would eliminate completely remove cloud pixels (Reproduced from Ref. 44).

the MODIS daily cloud-free snow product composite of the Qinghai–Tibet Plateau, China, on February 18, 2011.

3.2 *Fraction of Snow Cover*

Traditional snow cover mapping methods treat all pixels as uniform. Although the NDSI-based method has improved estimation accuracy as compared with other methods, it is still limited by the mixed pixel problem and is thus unable to meet the precision requirement for snow characteristics at local or basin scales. Thus, a more accurate snow cover fraction (SCF) map is desired over a traditional binary snow map.

At present, three types of approaches have been developed for deriving the SCF: statistical regression, spectral unmixing, and machine learning.

Statistical regression is the most widely used type; it establishes a unified regression model based on the relationship between the SCF and reflectance/NDSI.[46–52] MODIS SCF products from the NSIDC, such as MOD10A1 for Terra and MYD10A1 for Aqua, were produced using statistical regression. In China, Jin et al. modified the parameters of the subpixel SCF model proposed by Salomonson.[51] They retrieved the subpixel SCF from MODIS data using CBERS-2 CCD data as ground truth in Northeast China.[53] Zhang et al.[54] also established a linear relationship model between SCF and NDSI using HJ-1B data as ground truth. The precision of the linear regression using a single value of the NDSI is low, where the SCF is near 1 or 0. To solve this problem, the relationship between the SCF and multiple factors can be defined; Cao and Liu[55] developed a linear relationship model between SCF, NDSI, and NDVI to improve snow detection in forests. Moreover, several different segmentation methods were also proposed to determine SCF, which were validated by using ETM+ or HJ-1B CCD/IRS images. Findings show that the product generated using the segmentation method is improved, as compared with the MOD10A1/SCF product.[56–58] Additionally, Liu et al.[59] proposed a nonlinear regression model to retrieve the SCF based on the NDSI. Tang et al.[60] considered different land cover types and developed a subpixel snow mapping algorithm for the Qinghai–Tibet Plateau using MODIS data and linear regression. The statistical regression model is simple and easy to operate. However, this method is limited and difficult to apply due to large differences in the model parameters, which are caused by factors such as different land cover types and regions and the physical state of the snow.

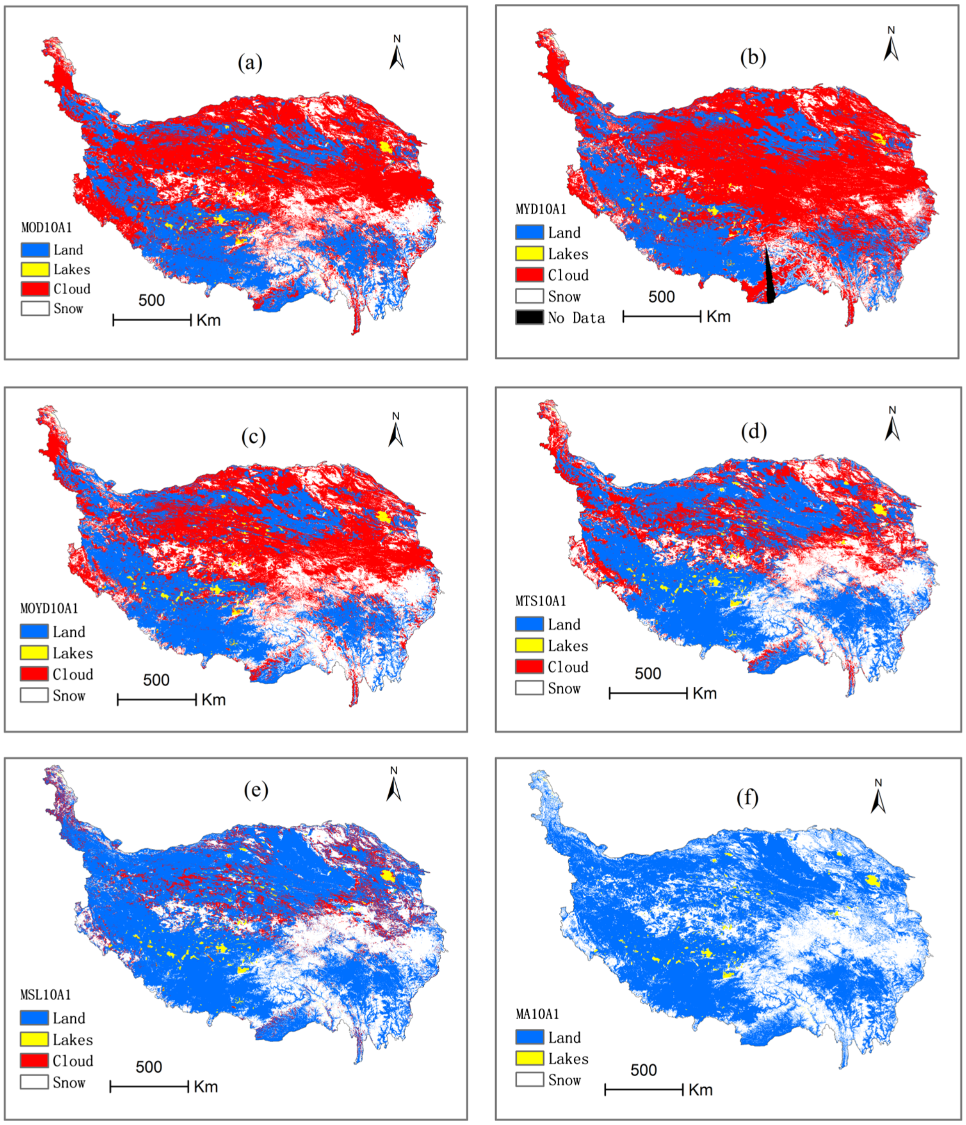

Fig. 2 MODIS daily cloud free snow product composite process in the Qinghai–Tibet Plateau, China, on February 18, 2011. (a) is the MODIS snow cover product from Terra, (b) is the MODIS snow cover product from Aqua, (c) is the composite of Terra and Aqua snow cover product, (d) is the adjacent temporal composite, (e) is the interpolation using SnowL methods, (f) is the composite of results of (e) and AMSR-E snow water equivalent products. Each step was considered as the input of next step. (Reproduced from Ref. 45).

Spectral unmixing is another widely used method, which creates a hybrid, simulated spectrum and estimates the mixed reflectance for each pixel in each frequency band. The reflectance of each mixed pixel is then calculated as a function of the spectral endmember.[61–67] Linear spectral mixture analysis is the most commonly used spectral unmixing method, which regards the observed reflectance as a linear combination of reflectance from certain surface constituents. Liang et al.[68] used a linear mixture spectrum disassembling method to study the snow coverage rate and spatial classification for four NOAA satellite images under sunny conditions during two snow disasters in China from 1996 to 1997. Pei et al.[69] used a linear spectrum mixing model to extract the SCF in the northern Xinjiang Region from MODIS imagery. Chen et al.[70] extracted snow area at a subpixel scale using a linear spectral mixture model from MOD02HKM imagery. Zhu et al.[71] retrieved the subpixel snow-covered area for the Qinghai–Tibet Plateau from MODIS data by employing a linear spectral mixture method based on multiple-endmember spectral analysis. Zhang[72] tested one linear mixture model (LMM) and three different nonlinear subpixel analysis methods: fuzzy c-means clustering, back-propagation neural networks, and support vector machine (SVM). They concluded that the LMM and the SVM provided the best estimates of snow cover components. Notably, Hao et al.[73] validated the accuracy of four different subpixel analysis methods: linear regression, full-constrained linear mixed-pixel decomposition, sparse regression unmixing, and non-negative matrix unmixing, based on the known proportion of snow in Northern Xinjiang, China. A comparison of the above methods shows that the linear regression method has the lowest accuracy, especially when the snow proportion is less than 50%; the accuracy of the sparse regression algorithm and non-negative matrix factorization were slightly higher than the full-constrained linear mixed-pixel decomposition (Fig. 3). Better results could be obtained using other unmixing inversion algorithms; however, the computation will be very time consuming due to the large amount of remote sensing data. In general, the advantage of linear spectrum unmixing is that it can be easily modeled due to having a clear physical and scientific basis. The previous studies also confirm that the method gives a comparatively accurate estimation of snow. The main drawback of linear spectrum unmixing is the assumption that the same object in a pixel has the same spectral characteristics. However, the same object may yield different spectra; different objects can have the same spectrum. Thus, the selection of reasonable endmembers and reference spectral values can be problematic and may result in large errors. The nonlinear spectral unmixing model is generally more complex. Many of the model parameters are difficult to accurately determine, making it difficult to use in practice. In addition, the computational efficiency of the method is usually problematic for large data volumes.

Based on intelligent computing, a machine learning approach can be used to estimate the SCF as an alternative to regression and spectral unmixing. Dobreva and Klein[74,75] first investigated the applicability of three-layered feed-forward error back propagation artificial neural networks (ANN) to estimate MODIS SCF of flat areas in the Northern Hemisphere. Inspired by this, Hou and Huang[76] developed a three-layer feed-forward ANN for mountainous fractional snow cover (FSC) mapping using MODIS products [reflectance at seven bands, NDSI, land surface temperature (LST), and SCF], ETM+, and auxiliary topographic (elevation, slope, and aspect) data. They designed eight experimental schemes according to the different

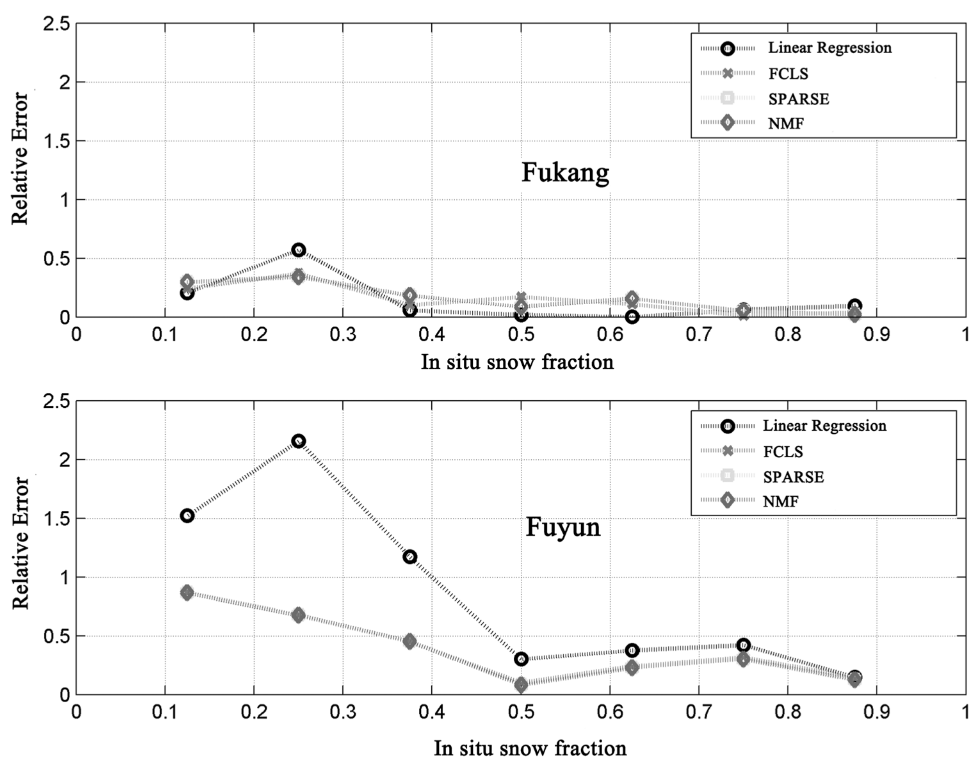

Fig. 3 The comparison of results of fractional snow cover between *in situ* measurements and the results from four spectral unmixed models from the Fukang and Fuyun study areas (Reproduced from Ref. 73).

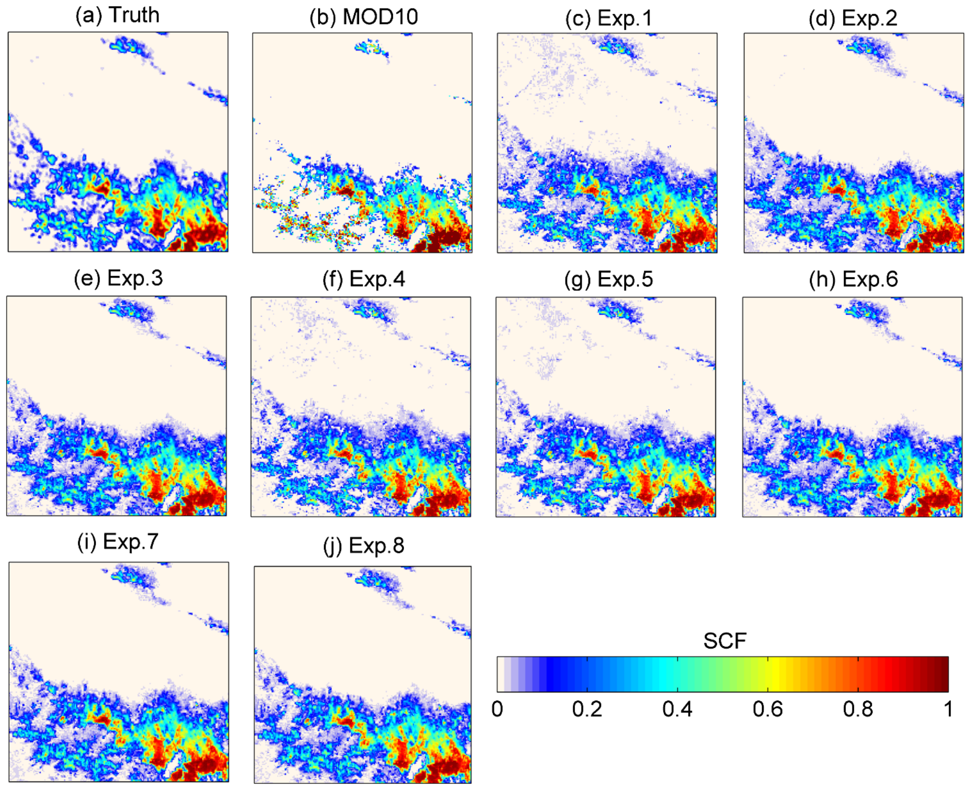

Fig. 4 Snow cover fraction (SCF) maps from (a) ground-truth derived from Landsat ETM+, (b) MOD10, and (c)–(j) results derived from different artificial neural network schemes on nonindependent Test1 (Reproduced from Ref. 76).

combinations of input components. Images from three time periods were chosen to train and validate the ANN; the proposed method was tested on three different test sets (nonindependent, temporal independent, and spatial-temporal independent) at the upper reaches of the Heihe River Basin. The SCF maps, derived from Landsat ETM+ reference values, MODIS SCF (MOD10), eight ANN schemes on nonindependent Test1 and spatial-temporal independent Test4, are shown in Fig. 4. The figure illustrates that the ANN can easily incorporate auxiliary information to improve the accuracy of mountainous FSC mapping with considerable generalization. However, a machine learning-based approach requires adequate representation of the training samples, which can be difficult to achieve. Additionally, due to the massive number of pixels in remote sensing images, the training set is very large, which often leads to unstable performance.

3.3 *Snow Grain Size*

Snow grain size is an important parameter that can indicate snow albedo change. It is also an important input factor of many snow and climate models. Satellite remote sensing of snow is critical for monitoring snow age, pollution levels, and grain sizes over difficult-to-access mountainous regions. Fundamental to all remote sensing algorithms is the relationship between the measured reflectance and the to-be-retrieved microphysics characteristics.

Over the past 20 years, many researchers have made use of remote sensing satellite images, such as TM and AVHRR, to retrieve snow grain size.[77–79] Nolin and Dozier[80] described a method for remotely sensing grain size from airborne visible / infrared imaging spectrometer (AVIRIS) data using the snow reflectance at 1.03 μm generated by the discrete ordinates radiative transfer (DISORT) program for a multilayered plane-parallel medium model and the wavelength of prominent ice absorption features. This method was sensitive to sensor noise and required knowledge of the solar and viewing geometries. Subsequently, a more robust algorithm[81] that integrated the absorption bands near the 1.03-μm wavelength (0.96 to 1.08 μm) minimized many effects of noise on grain size retrievals. Painter et al.[82,83] used a linear spectral unmixing

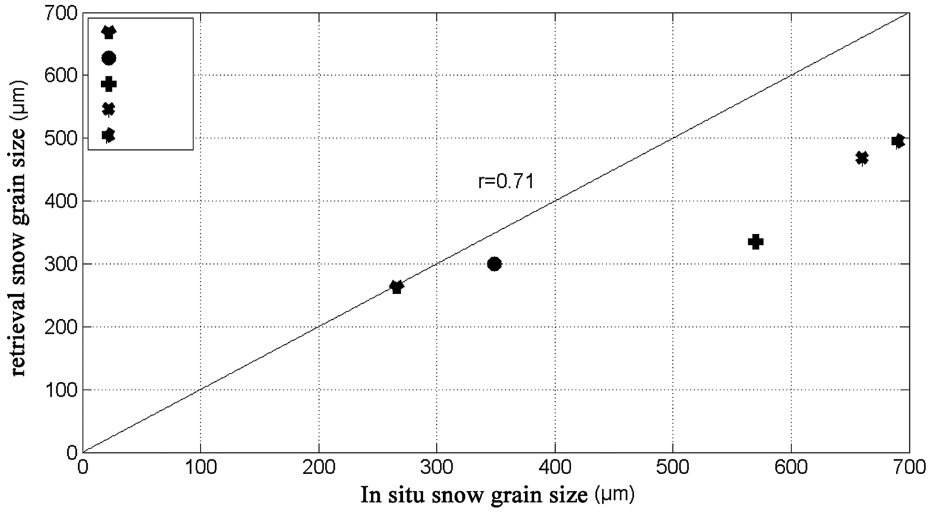

Fig. 5 Scatterplot showing the correlation between measured snow grain size and grain size derived from the asymptotic radiative transfer method (Reproduced from Ref. 93).

method to map relative grain size at subpixel resolution from AVIRIS data. Then, they developed MODSCAG (MODIS snow-covered area and grain size), which maps snow and its grain size simultaneously using spectral mixture analysis coupled with a radiative transfer model.

In China, there are also studies on retrieving snow grain size from remote sensing data. Hao et al.[84] retrieved snow grain size using three methods applied to HYPERION data over Qilian Mountain, China. The results of the three methods were compared with the *in situ* data of snow grain size, which were measured synchronously as the HYPERION sensor passed over the snowpack field.[85] Jiang et al.[86] also validated these methods using spectrum reflection data of snow in different grain sizes measured over the Binggou Basin. However, their methods generally used either the WW (Wiscombe–Warren) or DISORT model. They assume snow particles to be an equivalent sphere; Mie scattering (MIE) scattering theory is then used to model the optical characters of a single spherical snow particle. Nevertheless, as suggested by numerous experimental studies of microphysics snow properties, the snow pack should be considered as a multiple scattering, closely packed medium consisting of snow particles with irregular shapes.[87–90] Kokhanovsky et al.[91,92] developed an asymptotic radiative transfer (ART) model to model the snow spectra for different snow shapes and grain sizes. It simplified the traditional radiative transfer model, but without the loss of model accuracy. Hao et al.[93] developed an improved snow retrieval method using the ART model and the *in situ* spectral reflectance of different snow grain sizes. Finally, the method was validated using *in situ* snow grain size, which was used to calculate the equivalent snow grain size by the improved digital snow particle properties method. Figure 5 shows the validation results of the improved snow grain retrieval algorithm.

3.4 *Microwave Remote Sensing of Snow*

Seasonal snow cover plays an important role in hydrological cycles and climate processes.[94,95] The observations of sparse weather stations cannot meet the demand; thus, it is important to develop a retrieval method of snow depth or SWE from remote sensing data. Passive microwave remote sensing is the most efficient way to retrieve snow depth and SWE.

Snow depth retrieval can be influenced by the condition of snowpacks, such as snow crystal,[96–98] snow density,[99,100] and vegetation.[101] Inaccurate snow properties will lead to large errors in the retrieved snow depths. The global passive microwave snow depth retrieval algorithms did not consider these characteristics and overestimated snow depth in western China.[101,102]

Snow depth retrieval from passive microwave dates back to 1993 in China. Cao and Li[103] used scanning multichannel microwave radiometer (SMMR) data to develop a snow depth retrieval algorithm for high mountains, plateaus, low mountains, hills, and basins in western China. In order to meet the demands of climate and hydrological researchers, Che et al.[104]

developed a snow depth time series. Che et al. modified the Chang algorithm[105] and developed a relationship between the observed snow depth and passive microwave brightness temperature from SMMR and SSM/I, respectively. In this algorithm, the influence of forest on snow depth retrieval was removed by integrating the forest fraction into the algorithm. Because precipitation, cold deserts, and frozen ground have similar volume scattering with snowpack, they are initially discerned from snowpack using a decision tree.[106] This long-term daily snow depth data product was obtained via the WESTDC (the Environmental and Ecological Science Data Center for West China, http://westdc.westgis.ac.cn/). The data were used to analyze the interannual variations of snow depth in China and three stable snow cover regions [Northwest, Northeast, and Qinghai-Xizang (Tibet) Plateau] from 1978 to 2007;[104] updated results (2012) are shown in Fig. 6.

Since 2010, the microwave radiation instrument, carried on the FY-3B satellite, has provided brightness temperature data at the same frequencies as AMSR-E. Based on these data, a statistical relationship between snow depth and brightness temperature was developed for bare soil, grassland, and forest.[107] This relationship is used in the operational algorithm for developing snow depth and snow-water equivalent products at the Chinese Meteorological Administration.

Because snow properties vary in both space and time, static algorithms tend to underestimate snow depth in the early snow season and overestimate in the late snow season. Therefore, a dynamic algorithm is needed to accurately monitor snow depth variation in a snow season and requires seasonal information of snow properties. In China, Che et al.[104] calculated the effects on snow grain size and density due to seasonal variations and used an empirical offset to modify their respective influences. The snow depth data product (at the WESTDC) was further

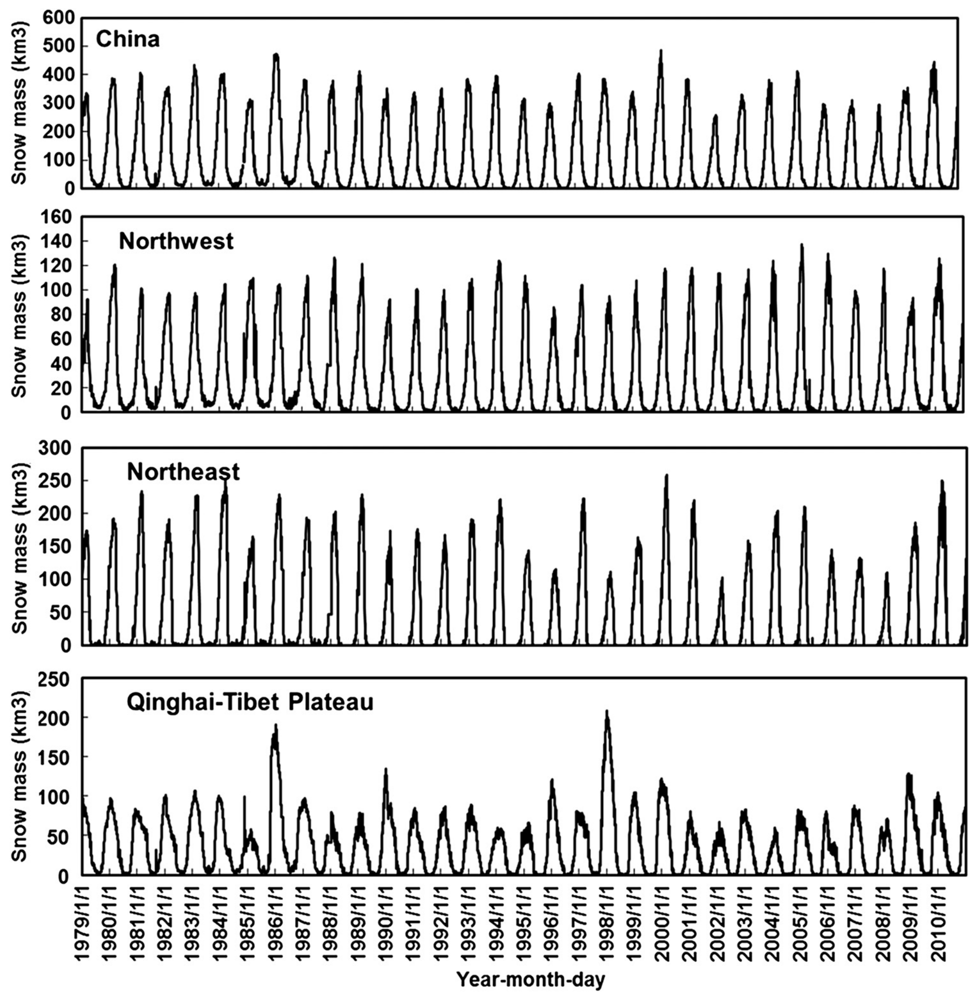

Fig. 6 Interannual variation of snow depth in China and three stable snows cover regions (Reproduced from Ref. 104).

updated using this dynamic algorithm. It has been downloaded more than 550 times (one file contains one year of snow depth data) by 337 registered users and has been used in many fields of research, such as spatiotemporal distribution of snow cover, climate change, ecologic change, cold region water cycle, and hydrological modeling.[108–110]

Detailed snow information was considered in the algorithm developed by Dai et al.[102] The authors investigated various properties of snow during different periods of a snow season and analyzed the seasonal snow depth and density variation based on 10 years of station data; finally, they obtained *a priori* snow characteristics (stratigraphy, snow grain size, density, and snow temperature) for Northwest China. The microwave emission model of layered snowpacks (MEMLS) model was used to simulate the snow brightness temperature based on the *a priori* snow characteristics; reference tables were then established showing the relationship between brightness temperature and snow depth. By considering detailed snow characteristics, the retrieval results were more accurate than other equivalent snow depth and snow water products.

When the dynamic algorithm developed in Northwest China was applied to Northeast China, the snow depth was underestimated due to the presence of large forested areas. The attenuation due to the presence of forest, and the associated upwelling radiation, can decrease the scattering signal from snow cover, causing an underestimation of snow depth in forested areas.[111–113] In order to eliminate the influence of forest on snow depth retrieval and improve retrieval accuracy in Northeast China, an optimal iterative method was used. Forest transmissivities at 18 and 36 GHz based on the microwave radiative transfer models of forest and snow were calculated, as well as snow properties measured from field experiments.[114] The results indicated that the transmissivities in forested areas in Northeast China are 0.656 and 0.895 at 18 and 36 GHz, respectively. The reference tables linking brightness temperature and snow depth in forested areas were built, which allowed for the estimation of the snow depths.

Topography is another factor that influences snow depth retrieval using passive microwave data. Jiang combined the Dense Media Radiative Transfer Theory and Advanced Integral Equation Model (AIEM) to simulate brightness temperatures of snowpacks.[115] Interface roughness was considered in the AIEM, which was then used to simulate the reflectivity on the soil/snow interface.

Since the electromagnetic wave absorption properties of water, the volume scattering of the snowpack is removed, and wet snow cannot be monitored by passive microwave. The strong absorption properties of wet snow are utilized by the synthetic aperture radar (SAR) to efficiently discern wet snow from other types of snow.[116] In the mid-1990s, Li et al.[117] examined the capability of snow-cover mapping with multifrequency and multipolarized SAR images from SIR-C.[117] Sun et al.[118] used multitemporal ENVSAT-ASAR images to characterize the seasonal variations of snow-covered landscapes in the upper reaches of the Heihe River Basin and retrieved the wet snow cover with a −2 dB threshold. Wen et al.[119] developed a snow depth retrieval algorithm based on ENVISAT-ASAR data by considering the microwave radiative transfer and the interaction between microwave radiation and the snow/soil interface. Moreover, the launch of interferometric SAR allowed for the mapping of snow cover using repeat pass SAR images.[120] However, most of the current methods can only retrieve wet snow cover area; a method to map total snow cover area has yet to be developed.

3.5 *Snow Data Assimilation*

Snow data assimilation provides a method to integrate all available observations related to snow variables into a land surface model to improve the estimation of variables, such as snow cover area, snow depth, and snow water equivalence. Because microwave remote sensing data can derive snow depth/SWE and optical remote sensing data can accurately obtain snow cover area, snow data assimilation usually focuses on how to assimilate microwave data on the basis of a radiative transfer model of snow and how to assimilate satellite-based snow cover area on the basis of an empirical relationship between snow cover area and snow depth. In China, the study of snow data assimilation is very limited and mainly conducted at CAREERI, CAS. With respect to snow radiance assimilation, the MEMLS has been integrated into the Chinese Land Data Assimilation System (CLDAS).[121] The CLDAS is capable of assimilating passive microwave brightness temperatures (i.e., AMSR-E and SSM/I) to improve snow depth and SWE estimates on the basis of ensemble Kalman filtering (EnKF). Huang et al.[122] analyzed the impacts of snow grain size and stratigraphy on snow radiance assimilation. They then developed an ensemble-based snow radiance assimilation method using an ensemble batch smoother to simultaneously characterize the SWE and soil freeze-thaw state by assimilating multifrequency active/passive microwave data.[123] Che et al.[124] developed a snow data assimilation scheme that directly assimilates passive microwave brightness temperature data into a snow process model. Results show that the data assimilation system can improve the estimation of snow depth in the accumulation period, but not in the ablation period. To better assimilate satellite-based snow cover products, Huang[125] developed and validated a technique to assimilate daily MODIS SCF products with an ensemble Kalman filter. Applied in the Xinjiang Province, the assimilation of MODIS SCF with an ensemble Kalman filter gave reasonable SCF values and improved snow depth estimation. Li et al.[126] assimilated MODIS snow cover area data and microwave snow depth data into a physically based snow model, using ensemble Kalman filtering to simulate snow distribution in regions where snow is patchy and shallow. Results show this method is applicable to other ungauged regions.

4 Experiments on Remote Sensing of Snow

A series of large observational experiments for land surface processes have played an important role in understanding earth systems from an experimental perspective, particularly in cold and arid regions. For example, under the framework of the climate and cryosphere project from 2002 to 2005, the cold land processes experiment was carried out to study the terrestrial cryosphere.[127] In China, scientists have realized the importance of these recent experiments in the development and innovation of remote sensing technology, development of algorithms, and validation of products. In China, experiments focusing on snow have been carried out with increasing frequency since 2007.

4.1 *Hydrological Remote Sensing in Cold Regions: a Ground-Based Synchronous Observation Experiment in the Upper Reaches of the Heihe River*

This experiment was one of three components of the Watershed Allied Telemetry Experimental Research (WATER) project. WATER was a multiscale land surface/hydrological experiment conducted in a cold and arid region in China. It was a simultaneous airborne, satellite-borne, and ground-based remote sensing experiment aiming to improve the observation ability, understanding, and predictability of hydrological and related ecological processes at a catchment scale.[128] In cold regions, hydrological remote sensing and a ground-based synchronous observation experiment in the upper reaches of the Heihe River were implemented from July 2007 to December 2009. The aim of the experiment was to understand hydrological processes and enhance the level of quantitative remote sensing in cold regions. Based on airborne remote sensing and ground-based tests, satellite-based remote sensing methods were developed and improved to extract hydrological process parameters for cold regions. The experiment was carried out in three areas (Binggou watershed, Arou grassland, and Biandukou) where land cover ages differed. Quantifying snow cover and frozen soil variables and parameters was the primary goal of the experiment (Table 1). Synchronous experiments occurred in four areas of different scales: watershed, sub-basin, hydrological unit, and pixel. In these areas, dense ground synchronous observation was jointly carried out with observations of fluxes and meteorological and hydrological elements. Aviation sensors containing a microwave radiometer, a hyperspectral imagery camera, a thermal infrared imagery camera, and a multispectral CCD camera collected a wealth of visible/near infrared, thermal infrared, active and passive microwave satellite data over the experimental areas (Tables 2 and 3). Through the experiments, an air-satellite-ground-based integrated dataset was built for the upper reaches of the river, which can be used to improve and validate land surface/hydrological process models in cold regions.

Table 1 The ground observation items in the simultaneous observation experiment.

Observations	Method	Objectives
Snow depth	Snow scale	Validation of remote sensing and radiative transfer models, input for hydrological models;
Snow temperature	Thermometer Hand-hold infrared thermometer	Validation of remote sensing and input for hydrological models;
Snow grain size	Hand-hold microscope	Idem
Snow liquid water content		Idem
Snow density	Snow gauge	Idem
Snow surface roughness	Roughness measuring plate	Validation of remote sensing
Snow brightness temperature	Ground-based microwave radiometer	Validation of airborne remote sensing and radiative transfer models;
Snow reflectivity	Spectrometer	Validation of airborne remote sensing;
Soil temperature	Thermometer Hand-hold infrared thermometer	Validation of remote sensing and input for hydrological models;
Soil moisture	Oven-drying method Soil moisture rapid determination method	Idem
Depth of freezing	Freezing pipe and GPR	Input for hydrological models;
Brightness temperature in soil freezing and thawing conditions	Ground-based microwave radiometer	Validation of airborne remote sensing and radiative transfer models;
Land surface roughness	Roughness measuring plate	Validation of remote sensing

Table 2 The information of airborne remote sensing in the simultaneous observation experiment.

Date	Instrument	Area	Objects
March 19, 2008	L and K band microwave radiometer	A'rou Biandukou	Soil freezing and thawing, soil moisture
March 21, 2008	L and K band microwave radiometer	Biandukou	Soil freezing and thawing soil moisture
March 22, 2008	Hyperspectral imager and CCD camaras	Binggou Watershed	Snow cover, snow albedo
March 24, 2008	Hyperspectral imager and CCD camaras	Binggou Watershed	Snow cover, snow albedo
March 29, 2008	K and Ka band microwave radiometer	Binggou Watershed	Snow depth, snow wetness
March 30, 2008	K and Ka band microwave radiometer	Binggou Watershed	Snow depth, snow wetness
April 1, 2008 Forenoon	L and K band microwave radiometer	A'rou	Soil freezing and thawing, soil moisture
April 1, 2008 Afternoon	L-band microwave radiometer and thermal imager	A'rou	Soil freezing and thawing, soil moisture

Table 3 The information of satellite remote sensing in the simultaneous observation experiment.

Date	Instrument	Area	Objects
October 17, 2007	ASAR	A'rou, E'bao, Biandukou	Soil freezing and thawing, soil moisture
October 18, 2007	ASAR	A'rou, E'bao	Idem
December 07, 2007	MODIS	Binggou Watershed	Snow cover, snow albedo
March 12, 2008	ASAR	A'rou, Biandukou	Soil freezing and thawing, soil moisture
March 14, 2008	ASAR	A'rou, Binggou Watershed	Soil freezing and thawing, soil moisture, snow depth, snow wetness
March 15, 2008	ASAR	A'rou, Binggou Watershed	Idem
March 21, 2008	ASAR	A'rou, Biandukou	Soil freezing and thawing, soil moisture
March 14, 2008	MODIS	Binggou Watershed	Snow cover, snow albedo
March 17, 2008	Hyperion and TM	Binggou Watershed	Idem
March 19, 2008	MODIS	Binggou Watershed	Idem

This experiment is the first remote sensing experiment in China to focus on snow and frozen soil, and it has had wide participation from snow remote sensing scientists in China. Twenty-six ground-based remote sensing sensors, with more than 100 supplementary instruments, were used to observe and monitor the land surface properties of snow and its variations.

4.2 *Cooperative Observation Series for Snow*

The snowfield measurement experiments were initially designed to investigate snow properties of typical snow areas in China, such as the North Xinjiang in China, Qinghai–Tibet Plateau, and the Northeast of China. The experiments are composed of a series of long-term snow surveys, primarily conducted every year, with joint collaboration from different universities and institutes. Thus, the snowfield measurement experiments were termed the COSS. The first experiment was carried out in the daytime at two snow fields, located in Fukang and Fuyun Counties of the North Xinjiang from December 1, 2010, to December 15, 2010. The purpose of this experiment was to develop retrieval methods of snow properties based on the quantitative understanding of measurements. First, blending methods of optical and passive microwave remote sensing techniques on snow were explored using multiple observations coincident in time and location. Second, the passive microwave signal responding to heterogeneous snow depth was measured, and the relationship was studied. In addition, quantitative observations of interactions between the snow optical spectrum, snow grain size, snow albedo, snow dust, and black carbon (BC) were made. As we know, optical and microwave signal responses from remote sensors are influenced by factors such as snow depth, density, wetness, crystal size and shape, and ice crusts, among others. To better understand these factors, we measured snow layer properties in snow pits, including snow depth, snow density, wetness, snow grain size, snow temperature, snow albedo, snow spectral, and snow microwave brightness temperatures. Snow samples were collected to analyze the content of snow dust and snow BC (Table 4). All of the airborne datasets described here and detailed information for data collection and processing are available online (http://westdc.westgis.ac.cn/).

In order to quantify the influence of forested areas on the estimation of snow depth, fieldwork was carried out in northeast China in January and March 2012 and in January 2013. Each time, snow transects through both forested and nonforested regions were designed, and snow properties along the transects were measured, including snow depth, snow density, grain size, temperature, and stratigraphy.

Table 4 Snow properties, measurement methods and objectives on Cooperative Observation Series for Snow (COSS).

Snow properties	Measurement methods	Objectives
Snow depth	Snow scale	Validation of remote sensing and radiative transfer models; input for hydrological models
Snow density	Snowfork	Validation of remote sensing
Snow wetness	Snowfork	Validation of remote sensing
Snow grain size	LCD microscope	Validation of remote sensing and radiative transfer models
Snow temperature	Needle thermometer	Validation of remote sensing; Input for hydrological models
Snow albedo	CMP3	Validation of remote sensing and radiative transfer models
Snow spectral	SVC HR-1024	Validation of remote sensing and radiative transfer models
Snow microwave brightness temperature	Microwave radiometer	Validation of remote sensing and radiative transfer models
Snow dust	PSS AccuSizer 780A	Validation of remote sensing and radiative transfer models
Snow black carbon	DRI Model 2001A	Validation of remote sensing and radiative transfer models

5 Utilizing Remotely Sensed Snow Data to Model Hydrological Processes

Many efforts using various methods have been made to integrate remotely sensed snow data into hydrological processes in cold regions in China.

Method 1: Remotely sensed snow data are used as input to drive the model simulation. The degree-day factor method is the most common approach to model snowmelt runoff utilizing remotely sensed snow cover data. The Snowmelt Runoff Model (SRM),[129] based on the degree-day method, has been widely used in China.[130–136] Utilizing an improved degree-day method, a distributed snow hydrological model was developed.[137]

Method 2: A snow hydrological model is derived using meteorological forcing, and the simulated snow status is adjusted or assimilated by the remotely sensed snow data. Recently, research has demonstrated that the synthesis methods could be used for improving the modeling accuracy of snow distribution. Considering the high spatial heterogeneity and complexity of snow hydrological processes, RS data were inserted into this more physically based snow model.[126,138]

For example, Li and Wang[139] developed a physically based snow model to more accurately describe the snow distribution in regions where snow is patchy and shallow. In this model, an energy balance method and RS data were used to simulate a complete snow season. Plot-scaled observations of SWE and daily discharge were used to validate the simulated results (Fig. 7).

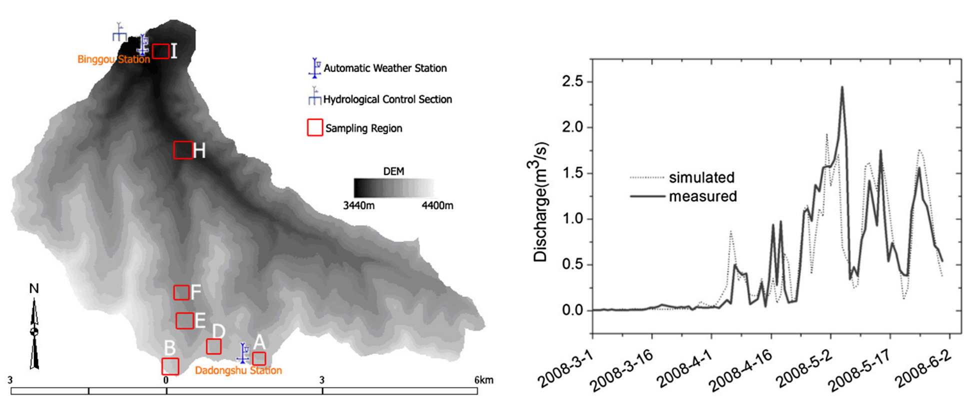

Fig. 7 The sampling regions for snow water equivalent observation (left) and the validation of daily discharges (Reproduced from Ref. 139).

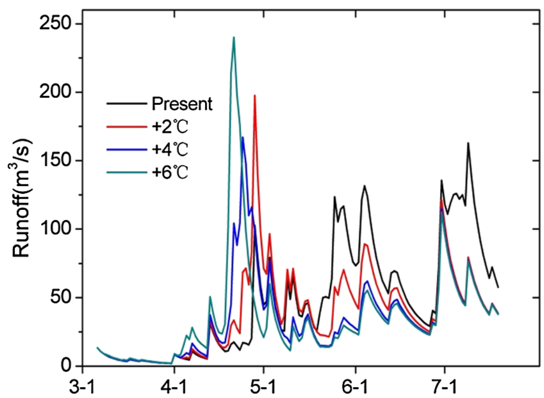

Fig. 8 Responses of snowmelt runoff to air temperature increases, +2°C, +4°C, and +6°C (Reproduced from Ref. 17).

This study demonstrated a large improvement by utilizing RS data in a physically based snow model.

RS data play an important role in evaluating the influence of climate change on snowmelt runoff.[140] In the upper basin of Heihe River in Northwestern China, Wang et al.[141] analyzed the influence of climate change on snow runoff using remotely sensed snow data with cloud removal. In the study, the SRM model was used to forecast the snowmelt runoff at catchment scales. The results showed an obvious antedisplacement of snowmelt runoff peaks and larger discharge as the response of snowmelt runoff to air temperature increased (Fig. 8). Remotely sensed snow data are very important for the calibration of models and scenario analysis in this study.

Modeling inhomogeneous spatial snow processes under complex terrain conditions utilizing remote sensing data is currently one of the most critical challenges in snow hydrology. Seasonal snow cover dominates in cold regions of China. Patch distribution, complex terrain, and inhomogeneous underlying conditions affect the modeling accuracy of spatial snow processes. Despite the development of several sophisticated, physically based snow schemes for the robust modeling of snow distribution, there is still high uncertainty and error due to scarce *in-situ* observations and inaccurate distributed meteorological data in ungauged mountainous regions. Exploring spatial information from remote sensing data is expected to enhance our understanding of complex snow hydrological processes.

6 Early Warning of Snow Disasters in Pastoral Areas

Snow has less of an impact on animal husbandry in developed countries due to better infrastructure in grasslands and within the livestock industry. As for snow disasters in pastoral areas in China, emphasis has been placed on monitoring the change of snow distribution and livestock loss postdisaster.[142] A natural disaster caused by continuous snowfall in winter and spring resulting in a large amount of livestock death is called a snow-caused livestock disaster or snow disaster.[143]

In 2006, the Chinese government issued a national standard for grading snow disasters in pastoral areas (GB/T 20482-2006) (General Administration of Quality Supervision of China, 2006). According to the standard, Zhou et al.[144] analyzed the potential conditions of snow disasters by evaluating the vulnerability of hazard-affected bodies and the dynamic change of precipitation in the natural environment. Liu et al.[145] did a preliminary study on an early warning system and hazard assessment models of snow disasters in pastoral areas of northern Xinjiang utilizing the livestock mortality rate as a factor of disaster assessment. Zhang et al.[146] proposed some indicators and methods to quantify those indicators for the early warning of snow disasters in pastoral areas of the northern Qinghai province. Moreover, early warning and risk assessment are the two most important yet complicated issues in the study of snow-caused livestock disasters. Li et al.[147] established a forecasting model of snow calamity on meteorology and a forecasting model of snow calamity on remote sensing based on the relation between the quantity of

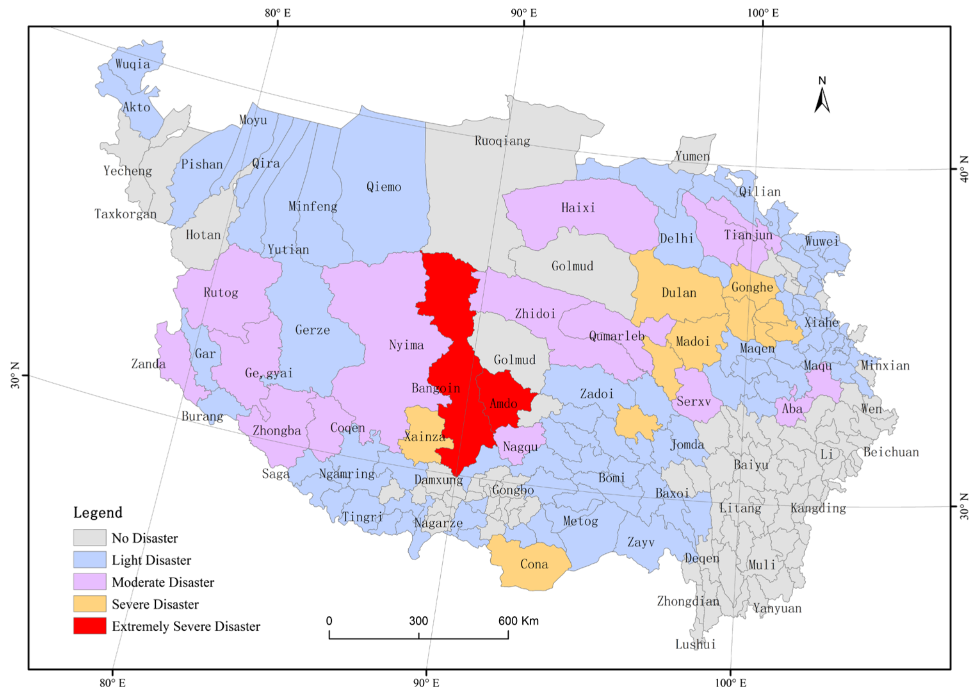

Fig. 9 Snow disaster warning simulation result (county basis) of TP in late January 2008 ($J = 12$) (Reproduced from Ref. 148).

precipitation and depth of snow using GIS and RS technologies. Wang et al.[148] developed a model for the early warning of snow-caused livestock disasters on a county basis and proposed a method of qualitative risk assessment of snow disasters at a 500-m resolution for pastoral areas on the Tibetan Plateau. They chose 411 cases, from 2008 to 2010, to validate the predicted results from the early warning model, which had an overall accuracy of 85.64% in predicting snow disasters and no disasters (Figs. 9 and 10).

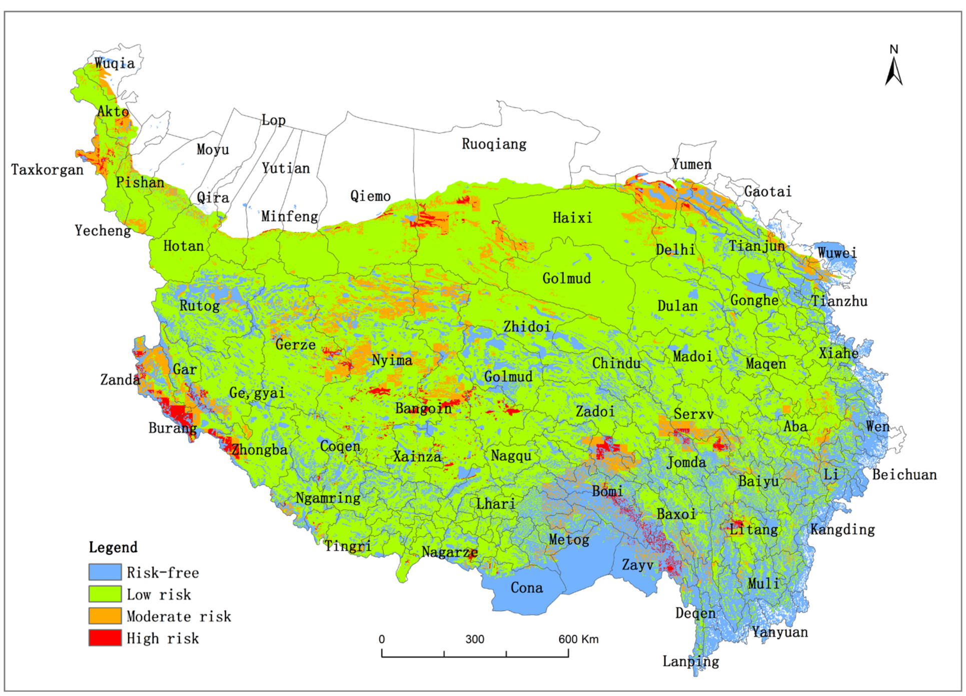

Fig. 10 Simulated risk intensity of snow disaster map at 500-m pixel scale in late January 2008 ($J = 12$) (Reproduced from Ref. 148).

7 Conclusions

Over the past 30 years, the research on remote sensing on snow in China has produced numerous encouraging achievements. Some datasets and products have been used with very promising results in several areas, such as hydrological modeling in cold regions, climate variation analysis, and snow disaster monitoring. However, innovative and effective algorithms and theories of remote sensing on snow in China are still needed to meet both scientific and operational requirements. Additionally, standardization and regularization of field experiments for snow remote sensing is important and pressing. Presently, limited observation fields including automatic weather stations and snow monitoring systems have been established in Northwestern China. A long-term plan has been initiated to build snow observation networks based on multi-organization cooperation. Meanwhile, a conference for remote sensing of snow in China will be held routinely every 2 years, which provides a fruitful academic exchange platform for promoting development and progress in this area.

For the coming years, two main topics have been proposed for development: retrieving BC distribution by satellite data and conducting allied telemetry experiments at the watershed scale.

1. BC in snow is a concern because light absorbing impurities, even in small quantities, can alter snowmelt time and snow spatial coverage by reducing snow reflectance; this is tightly coupled to climate through snow albedo feedback.[149–154] Although many researchers have simulated and estimated the impacts of climate on BC in snow,[155–157] the level of impact is still an ongoing focus due to different simulation results from different studies and the lack of experimental validation. Satellite data have irreplaceable advantages compared with field sampling in acquiring the spatial and temporal distributions of BC in snow and ice. Retrieving BC content in snow and ice by coupling remote sensing data and radiation transfer models is significant for improving energy balance models and climate change research. Up to now, several retrieval algorithms have been developed for high altitude regions, but where snow is usually deep, there have been very few comprehensive and measured validations.[158–165] Considering the above issues, we have conducted several controlled field experiments with the aim of revealing the effects of BC on snow reflectance. Furthermore, based on these experiments, we are aiming to develop a retrieval algorithm for BC concentration in snow and ice suitable for mid-latitude regions.
2. After the WATER experiment, a subsequent and more comprehensive experiment in the Heihe River Basin was carried out, which is named the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) project.[166] In HiWATER, the cold region experiment is one of the most important components. The new snow experiment will address observation, remote sensing, hydrological modeling, and assimilation in cold mountain regions. Snow depletion curves will be developed by field and airborne measurements, which will be used to convert the SCF from MODIS to snow water equivalent and will be assimilated into cold region hydrological models to better understand the snow melting process.

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References

1. A. G. Klein, D. K. Hall, and G. A. Riggs, "Improving snow cover mapping in forests through the use of a canopy reflectance model," *Hydrol. Process.* **12**(10), 1723–1744 (1998).

2. R. L. Armstrong and E. Brun, *Snow and Climate: Physical Processes, Surface Energy Exchange and Modeling*, Cambridge University Press, Cambridge (2008).
3. J. L. Foster and A. T. C. Chang, "Snow Cover," in *Atlas of Satellite Observations Related to Global Change*, pp. 361–370, Cambridge University Press, Cambridge (1993).
4. D. A. Robinson, F. D. Kenneth, and R. H. Richard, "Global snow cover monitoring: an update," *Bull. Am. Meteor. Soc.* **74**(9), 1689–1696 (1993).
5. P. Li and D. Mi, "Distribution of snow cover in China (In Chinese)," *J. Glaciol. Geocryol.* **5**(4), 9–17 (1983).
6. Y. Xie, Q. Zhao, and F. Wang, "The characteristics of snow change and the relation between snow change and climate- a case study of Urumqi area (In Chinese)," *J. Arid Land Resour. Environ.* **21**(9), 51–55 (2007).
7. W. Song, J. Yuan, and X. Chen, "The analysis of correlation between the inundation of the Changjiang river valley in 1998 and the anomaly snow cover of the Qing Zang plateau in winter (In Chinese)," *Meteorological* **26**(2), 11–14 (2000).
8. S. Zhang et al., "Studying the snow and snowmelt runoff using the NOAA-5 remote sensing data (In Chinese)," *Chin. Sci. Bull.* **25**(15), 700–702 (1980).
9. X. Chen, "A study for extracting snow-cover information from satallite remote sensing data (In Chinese)," *Remote Sens. Environ. China* **3**(2), 108–115 (1988).
10. X. Chen and Q. Zeng, "Satellite snow cover monitoring and snowmelt runoff prediction in the high alpine area of northwestern China," *Trans., Am. Geophys. Union*, **72**(41), 442–168 (1991).
11. Y. Lan and Q. Zeng, "Grey prediction method on snowmelt runoff in the Hexi area (In Chinese)," *J. Glaciol. Geocryol.* **19**(2), 154–160 (1997).
12. Z. Li et al., "Measurement of glacier variation in the Tibetan plateau using Landsat data," *Remote Sens. Environ.* **63**(3), 258–264 (1998).
13. J. Wang, Y. Ding, and S. Liu, "Simulation of the runoff recharged by snow melt water and rainwater in a mixed way in the alpine steppes in a spring (In Chinese)," *Arid Land Geogr.* **28**(4), 460–464 (2005).
14. A. Lu et al., "Principal component analysis of the snow disaster factors in the pastoral nagqu prefecture, Tibet region (In Chinese)," *J. Glaciol. Geocryol.* **19**(2), 180–185 (1997).
15. M. Cao, X. Feng, and D. Jin, "The several spectral reflection characteristics of snow (In Chinese)," *Chin. Sci. Bull.* **20**, 1259–1261 (1982).
16. Y. Jin, *Remote Sensing Theory of Electromagnetic Scattering and Radiation*, Science Press, Beijing (1993).
17. J. Wang et al., "The cold regions hydrological remote sensing and ground-based synchronous observation experiment in the upper reaches of Heihe river," *J. Glaciol. Geocryol.* **31**(2), 189–197 (2009).
18. F. S. Singer and R. W. Pohham, "Non-meteorological observations from weather satellites," *Astronaut. Aerosp. Eng.* **1**(3), 89–92 (1963).
19. A. Rango and J. Martinec, "Snow accumulation derived from modified depletion curves of snow coverage," in *Symposium on Hydrological Aspects of Alpine and High Mountain Areas*, Vol. 138, pp. 83–90, IAHS Press, Oxfordshire, UK (1982).
20. J. Dozier, "Snow reflectance from Landsat-4 thematic mapper," *IEEE Trans. Geosci. Remote Sens.* **GE-22**, 323–328 (1984).
21. D. K. Hall, G. A. Riggs, and V. V. Salomonson, "Development of methods for mapping global snow cover using moderate resolution imaging spectroradiometer data," *Remote Sens. Environ.* **54**(2), 127–140 (1995).
22. B. Ramsay, "Prospects for the interactive multisensor snow and ice mapping system (IMS)," in *Proc. of the 57th Eastern Snow Conf., Syracuse, NY, East Snow Conference*, Syracuse, New York, pp. 161–170 (2000).
23. A. Rango, "Snow hydrology processes and remote sensing," *Hydrol. Process.* **7**(2), 121–138 (1993).
24. D. Hall et al., "MODIS snow cover products," *Remote Sens. Environ.* **83**(1–2), 181–194 (2002).
25. Q. Zeng, M. Cao, and X. Feng, "Study on spectral reflectance characteristics of snow, ice and water at Northwest China," *Sci. China, Ser. B* **4**, 370–377 (1984).

26. M. Cao, X. Feng, and D. Jin, "Preliminary research on some characteristics of the spectral reflection of snow cover," *J. Glaciol. Geocryol.* **6**(3), 15–26 (1984).
27. H. Ma et al., "Snow cover monitoring and mapping using NOAA-AVHRR data," *Arid Land Geogr.* **21**(3), 73–80 (1998).
28. J. Wang, "Comparison and analysis on methods of snow cover mapping by using satellite remote sensing data," *Remote Sens. Technol. Appl.* **14**(4), 29–30 (1999).
29. J. Wang, "Research on spectral reflectance properties of snow using moderate resolution imaging spectrodiometer data," *J. Glaciol. Geogryol.* **22**(2), 165–170 (2000).
30. X. Xiao, Z. Shen, and X. Qin, "Assessing the potential of VEGETATION sensor data for mapping snow and ice cover: a Normalized Difference Snow and Ice Index," *Int. J. Remote Sens.* **22**(13), 2479–2487 (2001).
31. X. Xiao et al., "Large-scale observations of alpine snow and ice cover in Asia: using multi-temporal VEGETATION sensor data," *Int. J. Remote Sens.* **23**(11), 2213–2228 (2002).
32. H. Yan, "Detecting snow and estimating snowpack parameters from NOAA16-AVHRR data," *J. Glaciol. Geocryol.* **26**(3), 369–373 (2004).
33. S. Li, H. Yan, and C. Liu, "Study of snow detection using FY-2C satellite data," *J. Remote Sens.* **11**(3), 406–413 (2007).
34. X. Hao et al., "Evaluation and comparison of MODIS and VEGETATION snow cover products in Northern Xinjiang, China," *Remote Sens. Technol. Appl.* **24**(5), 603–610 (2009).
35. X. Hao and J. Wang, "Evaluation of the NDSI threshold value in mapping snow cover of MODIS—a case study of snow in the middle Qilian Moutains," *J. Glaciol. Geocryol. Geocryol.* **30**(1), 132–138 (2008).
36. W. Yang et al., "Analysis of leaf area index products from combination of MODIS Terra and Aqua data," *Remote Sens. Environ.* **104**(3), 297–312 (2006).
37. X. Wang et al., "Comparison and validation of MODIS standard and new combination of terra and aqua snow cover products in Northern Xinjiang, China," *Hydrol. Process.* **23**(3), 419–429 (2009).
38. H. Xie, X. Wang, and T. Liang, "Development and assessment of combined Terra and Aqua snow cover products in Colorado Plateau, USA and northern Xinjiang, China," *J. Appl. Remote Sens.* **3**, 033559 (2009).
39. X. Wang and H. J. Xie, "New methods for studying the spatiotemporal variation of snow cover based on combination products of MODIS Terra and Aqua," *J. Hydrol.* **371**(1–4), 192–200 (2009).
40. Y. Gao et al., "Toward advanced daily cloud-free snow cover and snow water equivalent products from Terra-Aqua MODIS and Aqua AMSR-E measurements," *J. Hydrol.* **385**(1–4), 23–35 (2010).
41. Y. Gao, N. Lu, and T. Yao, "Evaluation of a cloud-gap-filled MODIS daily snow cover product over the Pacific Northwest USA," *J. Hydrol.* **404**(3–4), 157–165 (2011).
42. J. Parajka et al., "Regional snow-line method for estimating snow cover from MODIS during cloud cover," *J. Hydrol.* **381**(3–4), 203–212 (2010).
43. T. Liang et al., "Toward improved daily snow cover mapping with advanced combination of MODIS and AMSR-E measurements," *Remote Sens. Environ.* **112**(10), 3750–3761 (2008).
44. X. Hao, J. Wang, and Z. Li, "Blending snow cover products basing on MODIS and AMSR-E," *The ATBD of CEOP—AEGIS* (2011).
45. X. Huang et al., "Algorithms for cloud removal in MODIS daily snow products," *J. Glaciol. Geocryol. Geocryol.* **35**(5), 1118–1126 (2012).
46. J. Barton, D. Hall, and G. Riggs, "Remote sensing of fractional snow cover using Moderate Resolution Imaging Spectroradiometer (MODIS) data," in *Proc. of the 57th Eastern Snow Conf.*, Syracuse, New York, pp. 171–183 (2000).
47. Y. J. Kaufman et al., "Remote sensing of subpixel snow cover using 0.66 and 2.1 μm channels," *Geophys. Res. Lett.* **29**(16), 28–21 (2002).
48. S. J. Metsämäki et al., "A feasible method for fractional snow cover mapping in boreal zone based on a reflectance model," *Remote Sens. Environ.* **95**(1), 77–95 (2005).

49. S. Metsämäki et al., “An optical reflectance model-based method for fractional snow cover mapping applicable to continental scale,” *Remote Sens. Environ.* **123**, 508–521 (2012).
50. S. Metsämäki, “A fractional snow cover mapping method for optical remote sensing data, applicable to continental scale,” Dissertation for the degree of Doctor of Science in Technology, Aalto University, School of Engineering, Department of Real Estate, Planning and Geoinformatics (2013).
51. V. V. Salomonson and I. Appel, “Development of the aqua MODIS NDSI fractional snow cover algorithm and validation results,” *IEEE Trans. Geosci. Remote* **44**(7), 1747–1756 (2006).
52. V. V. Salomonson and I. Appel, “Estimating fractional snow cover from MODIS using the normalized difference snow index,” *Remote Sens. Environ.* **89**(3), 351–360 (2004).
53. C. Jin et al., “Retrieval and validation of MODIS sub-pixel snow fraction in Northeast China,” *Remote Sens. Technol. Appl.* **23**(2), 195–202 (2008).
54. X. Zhang et al., “Sub-pixel snow coverage and correlation factors analysis based on MODIS and HJ-1-B data,” *Resour. Environ. Yang tze Basin* **19**(5), 566–571 (2010).
55. Y. Cao and C. Liu, “A simplified algorithm for extracting subpixel snow cover information from MODIS Data,” *J. Glaciol. Geocryol. Geocryol.* **28**(4), 562–567 (2006).
56. Z. Sun, Z. Liu, and D. Qiu, “Mehods of extracting snow cover information base on HJ-1B data: a case of the Juntanghu watershed,” *Arid Land Geogr.* **35**(1), 125–132 (2012).
57. Y. Zhang et al., “Validation and algorithm redevelopment of MODIS daily fractional snow cover products,” *Arid Zone Res.* **30**(5), 808–814 (2013).
58. Q. Zhou et al., “Algorithm for MODIS subixel snow fraction,” *J. Grad. Sch. Chin. Acad. Sci.* **26**(3), 383–388 (2009).
59. L. Liu et al., “Estimating fractional snow cover based on nonlinear NDSI model,” *Geomatics Inf. Sci. Wuhan Univ.* **37**(5), 534–536 (2012).
60. Z. Tang et al., “Estimating sub-pixel snow cover from MODIS in Qinghai-Tibet Plateau,” *J. Arid Land Resour. Environ.* **27**(11), 33–38 (2013).
61. J. M. Bioucas-Dias et al., “Hyperspectral unmixing overview: geometrical, statistical, and sparse regression-based approaches,” *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **5**(2), 354–379 (2012).
62. N. Foppa et al., “Operational sub-pixel snow mapping over the Alps with NOAA AVHRR data,” *Ann. Glaciol.* **38**(1), 245–252 (2004).
63. T. H. Painter et al., “Retrieval of subpixel snow covered area, grain size, and albedo from MODIS,” *Remote Sens. Environ.* **113**(4), 868–879 (2009).
64. T. H. Painter et al., “Retrieval of subpixel snow-covered area and grain size from imaging spectrometer data,” *Remote Sens. Environ.* **85**(1), 64–77 (2003).
65. P. Romanov, “Mapping and monitoring of the snow cover fraction over North America,” *J. Geophys. Res.* **108**(D16), 1–14 (2003).
66. D. Vikhamar and R. Solberg, “Subpixel mapping of snow cover in forests by optical remote sensing,” *Remote Sens. Environ.* **84**(1), 69–82 (2003).
67. D. Vikhamar and R. Solberg, “Snow-cover mapping in forests by constrained linear spectral unmixing of MODIS data,” *Remote Sens. Environ.* **88**(3), 309–323 (2003).
68. T. Liang et al., “Snow classification and monitoring models in the pastoral areas of the northern Xinjiang,” *J. Glaciol. Geocryol. Geocryol.* **26**(2), 160–165 (2004).
69. H. Pei et al., “Remote sensing-based monitoring of coverage and depth of snow in northern Xinjiang,” *J. Nat. Disasters* **17**(5), 52–58 (2008).
70. X. Chen et al., “A study on methods and accuracy assessment for extracting snow covered areas from MODIS images based on pixel unmixing, a case on the middle of the Tianshan Mountain,” *Resour. Sci.* **32**(9), 1761–1768 (2010).
71. J. Zhu, J. Shi, and Y. Wang, “Subpixel snow mapping of the Qinghai–Tibet Plateau using MODIS data,” *Int. J. Appl. Earth Obs.* **18**, 251–262 (2012).
72. H. Zhang, “Moderate sub-pixel snow mapping algorithm on Tibetan-Plateau,” in *Grad. Sch. Chin. Acad. Sci.*, Institute of Remote Sensing Aplications, Beijing (2004).
73. X. Hao et al., “Observations of snow mixed spectral characteristics using a ground-based spectral radiometer and comparing with unmixing algorithms,” *Spectrosc. Spectral Anal.* **32**(10), 2753–2758 (2012).

74. I. D. Dobreva and A. G. Klein, "Fractional snow cover mapping through artificial neural network analysis of MODIS surface reflectance," *Remote Sens. Environ.* **115**(12), 3355–3366 (2011).
75. I. D. Dobreva and A. G. Klein, "Artificial neural networks approach to fractional snow cover mapping," in *66th Eastern Snow Conf. Niagara-on-the-Lake*, Ontario, Canada (2009).
76. J. Hou and C. Huang, "Improving mountainous snow cover fraction mapping via artificial neural networks combined with MODIS and ancillary topographic data," *IEEE Trans. Geosci. Remote* (2013).
77. J. Dozier, S. Schneider, and D. F McGinnis, "Effect of grain size and snowpack water equivalence on visible and near-infrared satellite observations of snow," *Water Resour. Res.* **17**(4), 1213–1221 (1981).
78. J. Dozier and D. Marks, "Snow mapping and classification from Landsat Thematic Mapper data," *Ann. Glaciol.* **9**, 97–103 (1987).
79. B. Bourdelles and M. Fily, "Snow grain-size determination from Landsat imagery over Terre Ade'lie, Antarctica," *Ann. Glaciol.* **17**, 86–92 (1993).
80. A. Nolin and J. Dozier, "Estimating snow grain size using AVIRIS data," *Remote Sens. Environ.* **44**(2–3), 231–238 (1993).
81. A. Nolin and J. Dozier, "A hyperspectral method for remotely sensing the grain size of snow," *Remote Sens. Environ.* **74**(2), 207–216 (2000).
82. T. Painter et al., "The effect of grain size on spectral mixture analysis of snow-covered area from AVIRIS data," *Remote Sens. Environ.* **65**(3), 320–332 (1998).
83. T. Painter et al., "Retrieval of subpixel snow-covered area and grain size from imaging spectrometer data," *Remote Sens. Environ.* **85**(1), 64–77 (2003).
84. X. Hao, J. Wang, and T. Che, "The measurement and analysis of the snow spatial distribution and properties in Qilian-Binggou watershed, China," *J. Glaciol. Geocryol. Geocryol.* **31**(2), 284–292 (2009).
85. X. Hao, "Retrieval of alpine snow cover area and grain size basing on optical remote sensing Title of your thesis," Ph.D. Thesis, Cold and Arid Region Environment and Engineer Research Institute, China Academy of Sciences, pp. 89–120 (2008).
86. T. Jiang, S. Zhao, and P. Xiao, "Spectral analysis of different snow grain sizes based on field measurement," *J. Glaciol. Geocryol. Geocryol.* **31**(2), 227–232 (2009).
87. T. Aoki et al., "Effects of snow physical parameters on shortwave broadband albedos," *J. Geophys. Res.* **108**, 4616–D19 (2003).
88. M. Matzl and M. Schneebeli, "Measuring specific surface area of snow by near infrared photography," *J. Glaciol.* **52**(179), 558–564 (2006).
89. M. Kerbrat et al., "Measuring the specific surface area of snow with x-ray tomography and gas adsorption: comparison and implications for surface smoothness," *Atmos. Chem. Phys.* **8**(5), 1261–1275 (2008).
90. E. Zege, I. Katsev, and A. Malinka, "Algorithm for retrieval of the effective snow grain size and pollution amount from satellite measurements," *Remote Sens. Environ.* **115**(10), 2674–2685 (2011).
91. A. Kokhanovsky and E. Zege, "Scattering optics of snow," *Appl. Opt.* **43**(7), 1589–1602 (2004).
92. A. Kokhanovsky and V. Rozanov, "The retrieval of snow characteristics from optical measurements," in *Light Scattering Reviews*, Vol. **6**, pp. 289331, Springer-Praxis, Chichester, UK (2011).
93. X. Hao et al., "The measurement and retrieval of the spectral reflectance of different snow grain size on Norther Xinjiang, China," *Spectrosc. Spectral Anal.* **33**(1), 0190–0195 (2013).
94. A. Simic et al., "Validation of VEGETATION, MODIS, and GOES+SSM/I snow cover products over Canada based on surface snow depth observations," *Hydrol. Process.* **18**(6), 1089–1104 (2004).
95. D. H. Qin, S. Y. Liu, and P. Li, "Snow cover distribution, variability, and response to climate change in western China," *J. Climate* **19**(9), 1820–1833 (2006).
96. A. W. England, "Thermal microwave emission from a scattering layer," *J. Geophys. Res.* **80**(32), 4484–4496 (1975).

97. A. T. C. Chang et al., "Microwave emission from snow and glacier ice," *J. Glaciol.* **16**(74), 23–39 (1976).
98. J. L. Foster, A. T. C. Chang, and D. K. Hall, "Comparison of snow mass estimates from a prototype passive microwave snow algorithm, a revised algorithm and snow depth climatology," *Remote Sens. Environ.* **62**(2), 132–142 (1997).
99. A. Wiesmann and C. Mätzler, "Microwave emission model of layered snowpacks," *Remote Sens. Environ.* **70**(3), 307–316 (1999).
100. J. L. Foster et al., "Quantifying the uncertainty in passive microwave snow water equivalent observations," *Remote Sens. Environ.* **94**(2), 187–203 (2005).
101. A. T. C. Chang et al., "The use of microwave radiometer data for characterizing snow storage in western China," *Ann. Glaciol.* **16**, 215–219 (1992).
102. L.Y. Dai et al., "Snow depth and snow water equivalent estimation from AMSR-E data based on a priori snow characteristics in Xinjiang, China," *Remote Sens. Environ.* **127**, 14–29 (2012).
103. M. Cao and P. Li "Evaluation and primary application of microwave remote sensing SMMR-derived snow cover in Western China (In Chinese)," *Remote Sens. Environ. China* **8**(4), 260–269 (1993).
104. T. Che et al., "Snow depth derived from passive microwave remote-sensing data in China," *Ann. Glaciol.* **49**, 145–154 (2008).
105. A. T. C. Chang, J. L. Foster, and D. K. Hall, "Nimbus-7 SMMR derived global snow cover parameters," *Ann. Glaciol.* **9**, 39–44 (1987).
106. N. Grody and A. Basist, "Global identification of snowcover using SSM/I measurements," *IEEE Trans. Geosci. Remote Sens.* **34**(1), 237–249 (1999).
107. L. Jiang et al., "Improvement of snow depth retrieval for FY3B-MWRI in China," *Sci. China Earth Sci.* **57**(6), 1278–1292 (2014).
108. J. Gao et al., "Spatiotemporal distribution of snow in eastern Tibet and the response to climate change," *Remote Sens. Environ.* **121**, 1–9 (2012).
109. Z. Yu et al., "Effects of seasonal snow on the growing season of temperate vegetation in China," *Global Change Biol.* **19**(7), 2182–2195 (2013).
110. G. Zhang et al., "Reply to Shen et al.: no evidence to show nongrowing season NDVI affects spring phenology trend in the Tibetan Plateau over the last decade," *Proc. Natl. Acad. Sci. U. S. A.* **110**(26), E2330–E2331 (2013).
111. D. K. Hall, J. L. Foster, and A. T. C. Chang, "Measurement and modeling emission from forested snowfields in Michigan," *Nordic Hydrol.* **13**(3), 129–138 (1982).
112. J. L. Foster et al., "Derivation of snow water equivalent in boreal forests using microwave radiometry," *Arctic* **44**(5), 147–152 (1991).
113. A. T. C. Chang, J. L. Foster, and D. K. Hall, "Effects of forest on the snow parameters derived from microwave measurements during the Boreas Winter Field Campaign," *Hydrol. Process.* **10**(12), 1565–1574 (1996).
114. T. Che, L. Dai, and X. Zheng, "Estimation of snow depth from MWRI and AMSR-E data in forest regions of Northeast China," *IEEE Trans. Geosci. Remote Sens.* (2013), in review.
115. L. Jiang, J. Shi, and L. Zhang, "On improvement of snow water equivalence estimation for passive microwave instrument-AMSR/E," *J. Remote Sens.* **11**(5), 677–685 (2007).
116. T. Schellenberger et al., "Wet snow cover mapping algorithm based on multitemporal COSMO-SkyMed X-band SAR images," *IEEE J. Stars* **5**(3), 1045–1053 (2012).
117. Z. Li, Q. Zeng, and W. Sun, "A study of snow-cover mapping with SAR image in the Tianshan Mountains (In Chinese)," *J. Glaciol. Geocryol. Geocryol.* **18**(4), 366–372 (1996).
118. S. Sun et al., "Snow cover area retrieval using C-band SAR in mountain areas (In Chinese)," *Remote Sens. Technol. Appl.* **28**(3), 444–452 (2013).
119. J. Wen et al., "Extent and depth of snow cover over the Nyainq ntanghla range derived from ASAR and MODIS data (In Chinese)," *J. Glaciol. Geocryol.* **28**(1), 55–61 (2006).
120. Z. Li et al., "SAR interferometry coherence analysis and snow mapping," *J. Remote Sens.* **6**(5), 334–338 (2002).
121. X. Li et al., "Development of a Chinese land data assimilation system: its progress and prospects," *Progr. Nat. Sci.* **17**(8), 881–892 (2007).

122. C. Huang et al., "Assessment of grain-size model and stratigraphy representation impacts on snow radiance assimilation: forward modeling evaluation," *IEEE Trans. Geosci. Remote Sens.* **50**(11), 4551–4564 (2012).
123. S. Bateni et al., "Feasibility of characterizing snowpack and the Freeze-Thaw state of underlying soil using multifrequency active/passive microwave data, *IEEE Trans. Geosci. Remote Sens.* **51**(7), 4085–4102 (2013).
124. T. Che et al., "Assimilating passive microwave remote sensing data into land surface modeling to improve the estimation of snow depth," *Remote Sens. Environ.* **143**(5), 54–63 (2013).
125. C. Huang, "Assimilation of MODIS snow cover fraction for improving snow variables estimation in west China," *Proc. SPIE* **8531**, 853111 (2012).
126. H. Li et al., "Synthesis method for simulating snow distribution utilizing remotely sensed data for the Tibetan Plateau," *J. Appl. Remote Sens.* **8**(1), 084696 (2013).
127. K. Elder et al., "NASA cold land processes experiment (CLPX 2002/03): field measurements of snowpack properties and soil moisture," *J. Hydrometeor.* **10**(1), 320–329 (2009).
128. X. Li et al., "An integrated remote sensing experiment on hydrological and ecological processes in the Heihe River Basin," *Adv. Earth Sci.* **27**(5), 481–498 (2012).
129. J. Martinec, A. Rango, and R. Roberts, "SRM snowmelt runoff model user's manual," E. Gómez-Landesa and M. P. Bleiweiss, eds., New Mexico State University, Las Cruces, New Mexico (2008).
130. S. Zhang and Q. Zeng, "Application of NOAA/TIROS satellite data to snowmelt-runoff model of Heihe Basin in Qilian Mountain," *J. Glaciol. Geocryol.* **8**(2), 119–130 (1986).
131. J. Wang and W. Li, "Establishing snowmelt runoff simulating model using remote sensing data and GIS in the west of China," *Int. J. Remote Sens.* **22**(17), 3267–3274 (2001).
132. H. Li and J. Wang, "The snowmelt runoff model applied in the upper Heihe River Basin," *J. Glaciol. Geocryol.* **30**(5), 769–775 (2008).
133. Y. Zhang et al., "Study on snowmelt runoff simulation in the Kaidu River basin," *Sci. China Ser. D: Earth Sci.* **50**(S1), 26–35 (2007).
134. Y. Dou et al., "The simulation of snowmelt runoff in the ungauged Kaidu River Basin of TianShan Mountains, China," *Environ. Earth Sci.* **62**(5),1039–1045 (2011).
135. Y. Liu and P. Zhang, "Analysis on the correlation between abundant or low runoff and Alpine snow cover based on remote sensing data—a case study of Manasi River Basin in Tianshan Mountain (In Chinese)," *Res. Soil Water Conserv.* **17**(3), 44–48 (2010).
136. X. Li and W. Williams Mark, "Snowmelt runoff modelling in an arid mountain watershed, Tarim Basin, China," *Hydrol. Process.* **22**(19), 3931–3940 (2008).
137. S. Fang et al., "Study on the distributed snowmelt runoff process based on RS and GIS," *J. Remote Sens.* **12**(4), 655–662 (2008).
138. Q. Zhao et al., "A snowmelt runoff forecasting model coupling WRF and DHSVM," *Hydrol. Earth Syst. Sci.* **13**(10), 1897–1906. (2009).
139. H. Li and J. Wang, "Simulation of snow distribution and melt under cloudy conditions in an Alpine watershed," *Hydrol. Earth Syst. Sci.* **15**(7), 2195–2203 (2011).
140. J. Wang and W. Li, "Establishing simulated model of snowmelt runoff for large scale basin in western China," *J. Glaciol. Geocryol.* **21**(3), 264–268 (1999).
141. J. Wang, H. Li, and X. Hao, "Responses of snowmelt runoff to climatic change in an inland river basin, Northwestern China, over the past 50 years," *Hydrol. Earth Syst. Sci.* **14**(10), 1979–1987 (2010).
142. X. Lu et al., "Principal component analysis of the snow disaster factors in the pastoral Nagqu prefecture, Tibet Region," *J. Glaciol. Geogryol.* **19**(2), 180–185 (1997).
143. T. G. Liang et al., "An evaluation approach for snow disasters in the pastoral areas of northern Xinjiang, PR China," *New. Zeal. J. Agr. Res.* **50**(3), 369–380 (2007).
144. R. Zhou, S. H. Shen, and F. X. Li, "A synthetical forcasting model of snow disaster in qinghai-tibet plateau," *Meteorological* **32**(9), 106–110 (2006).
145. X. Y. Liu et al., "Early warning and risk assessment of snow disaster in pastoral area of northern Xinjiang," *Chin. J. Appl. Ecol.* **19**(1), 133–138 (2008).
146. G. S. Zhang et al., "Study on warning indicator system of snow disaster and risk management in headwaters region," *Pratacultural Sci.* **26**(5), 144–150 (2008).

147. Z. Li et al., "Forecasting model of snow calamity and GIS application of special analysis technology in Qinghai Plateau," *J. Appl. Meteorol. Sci.* **18**(3), 373–379 (2007).
148. W. Wang et al., "Early warning of snow-caused disasters in pastoral areas on the Tibetan Plateau," *Nat. Hazard Earth Syst.* **13**(6), 1411–1425 (2013).
149. W. J. Wiscombe and S. G. Warren, "A model for the spectral albedo of snow, I: Pure snow," *J. Atmos. Sci.* **37**(12), 2712–2733 (1980).
150. S. G. Warren and W. J. Wiscombe, "A model for the spectral albedo of snow, II: Snow containing atmospheric aerosols," *J. Atmos. Sci.* **37**(12), 2734–2745 (1980).
151. S. G. Warren, "Impurities in snow: effects on albedo and snowmelt," *Ann. Glaciol.* **5**,177–179 (1984).
152. C. H. Twohy et al., "Light-absorbing material extracted from cloud droplets and its effect on cloud albedo," *J. Geophys. Res.* **94**(D6), 8623–8631 (1989).
153. B. Light et al., "The effect of included participates on the spectral albedo of sea ice," *J. Geophys. Res.* **103**(C12), 27739–27752 (1998).
154. M. G. Flanner et al., "Present-day climate forcing and response from black carbon in snow," *J. Geophys. Res.* **112**(D11), 16 (2007).
155. M. Z. Jacobson, "Climate response of fossil fuel and biofuel soot, accounting for soot's feedback to snow and sea ice albedo and emissivity," *J. Geophys. Res.* **109**(D21), 16 (2004).
156. J. Hansen et al., "Efficacy of climate forcings," *J. Geophys Res.* **110**(D18), 27 (2005).
157. Y. Qian et al., "Effects of soot-induced snow albedo change on snowpack and hydrological cycle in western United States based on Weather Research and Forecasting chemistry and regional climate simulations," *J. Geophys. Res.* **114**, D03108 (2009).
158. K. Stamnes et al., "ADEOS-II/GLI snow/ice products—Part I: scientific basis," *Remote Sens. Environ.* **111**(2–3), 258–273 (2007).
159. T. Aoki et al., "ADEOS-II/GLI snow/ice products—Part II: validation results using GLI and MODIS data," *Remote Sens. Environ.* **111**(2–3), 274–290 (2007).
160. M. Hori et al., "ADEOS-II/GLI snow/ice products—Part III: retrieved results," *Remote Sens. Environ.* **111**(2–3), 291–336 (2007).
161. E. P. Zege, A. P. Ivanov, and I. L. Katsev, *Image Transfer Through a Scattering Medium [M]*, Springer-Verlag, Heidelberg (1991).
162. E. P. Zege et al., "New algorithm to retrieve the effective snow grain size and pollution amount from satellite data," *Ann. Glaciol.* **49**(1), 139–144 (2008).
163. E. P. Zege et al., "Algorithm for retrieval of the effective snow grain size and pollution amount from satellite measurements," *Remote Sens. Environ.* **115**(10), 2674–2685 (2011).
164. A. A. Kokhanovsky and E. P. Zege, "Scattering optics of snow," *Appl. Opt.* **43**(7), 1589–1602 (2004).
165. R. Solberg et al., "Retrieving black carbon on snow and ice surfaces in the arctic," in *Proceedings of ESA Living Planet Symposium*, Bergen, Norway (2010).
166. X. Li et al., "Heihe watershed allied telemetry experimental research (HiWATER): scientific objectives and experimental design," *Bull. Am. Meteorol. Soc.* **94**(8), 1145–1160 (2013).

Jian Wang received his MSc degree in natural geography from the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences (CAS), Lanzhou, China, in 1989. He is currently a research scientist with the CAREERI, CAS, working on the remote sensing on snow hydrology and ecosystem service.

Hongxing Li is a PhD candidate with the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences. His current research interest focuses on snow remote sensing. His study focus on the effect of black carbon aerosol and other impurities in sown and ice on the variation of snow albedo.

Xiaohua Hao received his PhD degree in cartography and geography information system, from the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences (CAS), Lanzhou, China, in 2009. He is currently an assistant researcher with the CAREERI, CAS. His current research focus on the remote sensing retrieval of snow parameters.

Xiaodong Huang received a BS degree in geographic information system from the Lanzhou University in 2004, and a PhD degree in grassland science from the Lanzhou University, China in 2009. Currently, he is associate professor at Lanzhou University. His research interest is in snow cover monitoring using remote sensing technology. Other interests include surface hydrology, agriculture, and environment studies.

Jinliang Hou received the BS degree in computer science and technology from the Tianjin University of Technology and Education, China, in 2004, and the MS degree in computer science and technology from the China University of Petroleum, China, in 2011. She is currently a PhD candidate in laboratory of remote sensing and geospatial science at the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences (CAS), China.

Tao Che received a BS in geography information systems and cartography from Northwest University, Xi'an, China, in 2000, and a PhD in cartography and geography information systems from the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, in 2006. His work mainly focuses on remote sensing of cryosphere, data assimilation, and the field campaign by using ground, airborne, and satellite remote sensing data.

Liyun Dai received his PhD degree in cartography and geographic information systems from the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China, in 2013. Her main research focus is the remote sensing of the cryosphere, and her research interests include passive microwave remote sensing of snow, the analysis of snow variation and its influence on climate, microwave radiation transfer models, and geophysical inversion models.

Tiangang Liang is a professor and the director of the pastoral agriculture information laboratory in the College of Pastoral Agriculture Science and Technology, Lanzhou University. His research interest includes response and adaptation of alpine ecosystems to global change and snow disaster early warning.

Chunlin Huang received his PhD degree in cartography and geography information system from the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences (CAS), Lanzhou, China, in 2008. He is currently a researcher with the CAREERI, CAS. His current research activities concern hydrological data assimilation particularly for snow and soil moisture.

Hongyi Li received his PhD degree in cartography and geography information system, from the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences (CAS), Lanzhou, China, in 2009. He is currently an assistant researcher with the CAREERI, CAS. His current research includes the snow distribution simulation under complex terrain conditions and the remote sensing retrieval of snow parameters.

Zhiguang Tang received his MSc degree in cartography and geography information system from the Lanzhou University, Lanzhou, China, in 2011. Now he is a PhD candidate with the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences. His current research interest focuses on snow remote sensing.

Zengyan Wang received the BS degree in cartography and geography information system from Henan University in 2009 and the MS degree in GIS from Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, in 2012. She is currently pursuing the PhD degree in GIS and remote sensing at the Cold and Arid Regions Environmental and Engineering Research Institute.