Long-term snow disasters during 1982–2012 in the Tibetan Plateau using satellite data

Hang Yin a,b, Chunxiang Cao a, Min Xu a, Wei Chen a, Xiliang Ni a and Xuejuan Chen a

aInstitute of Remote Sensing and Digital Earth, State Key Laboratory of Remote Sensing Science, Chinese Academy of Sciences, Beijing, China; bUniversity of Chinese Academy of Sciences, Beijing, China

ABSTRACT
Taking the Tibetan Plateau (TP) as a study area, we developed an algorithm to generate long-term four-level snow disaster products (1982–2012) using a new daily snow depth product with a spatial resolution of 0.05° using AVHRR archival reflectance products (AVH09C1-version4) from Land Long-Term Data Record and passive microwave snow depth products. The total classification agreement of our products reached 83.6%, improved from 69.1%. R-square reached 0.62, which showed a good agreement with field data. Based on the products, we obtained annual snow disaster results during 1982–2012. The results indicated that in 1983, 1985, 1997, 1998 and 2008, a large part of the TP suffered extremely severe snow disaster. The annual variation of light and moderate snow disaster areas is much stable than severe and extremely severe areas. After 1999, annual extremely severe areas are more stable and smaller than before. Some areas suffered severe snow disaster in 1985, 1997 and 1998, while in other years they presented a normal status. A large part of the middle-east TP suffered extremely severe snow disaster almost every year. The information within population-filtered counties was extracted to support the development of the husbandry and the urban and rural planning for government.

1. Introduction
Cold high latitude and inland regions, such as the Tibetan Plateau, with harsh natural conditions and a long winter are subjected to natural disasters in a large number of regions since snow disasters frequently occurred in these areas. In pastoral areas, a great deal of snowfall will lead to grassland burying and transportation disruption, resulting in a large number of livestock deaths due to extremely low temperature and lack of forage stock. This has been a great influence on the sustainable development of animal husbandry in grassland. This has been a great influence on the sustainable development of animal husbandry in grassland. On the Tibetan Plateau (TP), with two of China’s four greatest pastures, the snow disasters, particularly the continuous snowfall in winter and spring, make the largest damage, especially including a large number of livestock deaths by continuous snowfall in winter and spring (Liang et al. 2007). In the autumn of 2008, a heavy snow disaster occurred in Madduo County of Qinghai Province and affected 27,052 livestock and 863 herders (http://news.xinhuanet.com/life/2008-11/12/content_10345196.htm). Harsh winter conditions, especially heavy snow can prevent livestock from accessing pastures and result in a large number of livestock deaths. According to the records, there have been 80 severe snow disasters in this region.
from 1956 to 1998 in Tibet. In Naqu County, snow disasters occurred in 74 months during October to next May from 1971 to 2001 (Zi 2007; Liu 2008).

Previous studies of heavy snow risk are limited to simple analyses of the historic meteorological station data (Zi 2007; Liu 2008) and supervised classification of manual labour. To find the characteristics of snow disasters on the TP, many studies focused on the long-term trend of historical snow disasters. Zhou et al. (2000) found the frequency of snow disasters increased after 1990 based on 1689 measured records from 26 stations in east TP. Dong et al. (2001) concluded that the snow disaster jumped to a very high frequency after 1993. Although meteorological stations provide us a long time-series data, there is a lack of spatial information, which makes remote sensing observation technology become more and more widely used. Besides, snow cover mainly exists in mountainous (Pu et al. 2007) or high-altitude areas on the TP, where meteorological stations are rare. Thus, the snow information from these stations may not accurately demonstrate the changes of snow variation for the entire TP. Remotely sensed data can provide spatial snow cover and depth information effectively and thus have been used in investigations of temporal and spatial snow cover variation for large areas. Currently, mainly passive microwave (PM), Advanced Very High Resolution Radiometer (AVHRR) and Moderate-resolution Imaging Spectroradiometer (MODIS) data-sets were used to analyze long-term variations of snow. However, the over coarse resolution of PM products will lead to significant information loss of snow cover analysis in regional scales. Lots of studies have been conducted using the MODIS snow products, while MODIS snow cover products are available only after 2000. Therefore, only AVHRR is able to provide 30 years’ remote sensing observations. Recently, the Long Term Data Record project (LTDR), funded by NASA, created a 0.05° global daily data-set. This LTDR version 4 covers the year 1982–2014, and includes improved atmospheric correction and inter-calibration between sensors. Until now, both AVHRR and PM data have provided continued support for more than 30 years’ observation with a very short revisiting period. Considering the advantages of the two long-term data, daily snow information can be extracted by effective algorithms.

Snow cover and snow depth are important parameters in studies of climate, surface radiation budget and hydrological cycle (Dressler et al. 2006; Gong et al. 2007). With appropriate models, it is also possible to extract the spatial–temporal pattern of snow disasters. We propose to improve snow depth extraction to get snow disaster data of each year, in order to assess the snow disaster risk on the TP and serve for government policy-making. The aim of our study is to find out how historical snow disasters distributed on the TP. The achieved results are further being tied to official historical records to analyze the TP snow disaster characteristics. An improved algorithm was developed to extract daily snow depth on the TP using LTDR data and PM snow depth products and test the accuracy of the new product. Then, snow disasters from 1982 to 2012 were derived from the products. Finally, both temporal and spatial characteristics of snow disasters on the TP were analyzed.

2. Study area

The TP (26°00’12”N–39°46’50”N and 73°18’52”E –104°46’59”E) is located in South-western China. Its major part is in Qinghai and Tibet provinces, with mean elevation over 4000 m, covering the highest pastoral areas in the world. The TP is not only the water head site of many Asian rivers (e.g. the Yellow, Yangtze and Lantsang rivers), but also one of the three major snowfall regions in China. It consists of 201 counties which belong to Qinghai, Xinjiang, Tibet, Gansu, Sichuan and Yunnan provinces, with a total area of 2.57 × 106 km², corresponding to 26.8% of the total areal extension of China (Figure 1) (Zhang et al. 2002). The TP has the unique alpine meadow in the world due to its specific geography, climate and natural conditions. It is an important habitat for yak, Tibetan sheep and many other rare wild animals. However, because of the undeveloped agriculture infrastructure in the region, heavy snow in winter and spring usually causes a large number of deaths of livestock due to cold weather and forage shortage. This has great adverse effects on the sustainable development of grassland animal husbandry.
3. Satellite data

3.1. LTDR–AVHRR

1982–2012 AVHRR archival reflectance products (AVH09C1-version4) from LTDR (http://ltdr.nasa.com.nas.com/cgi-bin/ltdr/ltdrPage.cgi) were used to derive daily products (AVH09C1-snow). Daily observations (snow depth) of 1998 from Chinese West Data Center are supported by Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences. Basic information of AVH09C1 is indicated in Figure 2.

3.2. PM snow depth products

The snow depth products for China were retrieved from the Scanning Multichannel Microwave Radiometer, the Special Sensor Microwave Imager, the Special Sensor Microwave Imager/Sounder and the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) from 1978 to present. These products were made by Che using his core algorithm improved from Chang’s. Based on radiative transfer process and Mie scattering mechanism, Chang calculated the relationship between snow depth and brightness temperature (BT) at 18 and 37 GHz horizontal polarization (Chang et al. 1987; Che et al. 2008). However, since the coefficients of Chang’s algorithm are constant, this algorithm is not suitable for the TP due to its unique characteristics. Che did a regression analysis utilizing an amount of test data of snow depth data and BT, which is more specific for the TP and has passed the verification of accuracy. As a result, we applied the Chinese Long Term Snow Depth Dataset (WDC-SD) supported by CAREERI, Chinese Academy of Science, China, to define the snow depth information (Che et al. 2008; Dai et al. 2012). The detailed information of WDC-SD is indicated in Figure 2.

4. Methodology

Several existing techniques were applied effectively for snow mapping: supervised spectral classification (Qobilov et al. 2001), artificial neural networks (Welch et al. 1992) and segmentation techniques.
However, these techniques are less effective at a regional scale, since they require intensive efforts in calibration and application. Threshold segmentation has been applied for the snow cover extraction for a long time, which makes it quite effective and mature.

A widely used approach to identify snow cover from satellite data employs normalized difference snow index (NDSI) (Hall et al. 2002). However, the NDSI method could not be applied to AVHRR data for years before 1998. It is necessary to construct another approach that can be used for early AVHRR data. Here, an automatic algorithm of snow mapping using AVHRR data was proposed for the study area to produce daily snow cover products (Figure 2).

1. **BT4 < BT4\text{max} (snow)**: This test defines the maximum brightness temperature that the class 'snow' can have. Objects warmer than this temperature are classified as ‘no-snow’.
2. **BT4 > BT4\text{min} (snow)**: This threshold gives the lowest expected BT for snow. It is used to eliminate clouds that are colder than the snow.
3. **BT4–BT5 < \triangle BT45 (cirrus)**: This test determines whether the density of cirrus clouds is sufficiently low for accurate snow classification. It defines the optical thickness of cirrus clouds from which a pixel is declared as ‘cloud’ and therefore is rejected from further snow tests. It is based on the fact that thick cirrus clouds cause a significant difference in BT between channels 4 and 5. However, a thin cirrus cover may allow snow to be properly detected.

Figure 2. Flow chart of the main algorithm about new snow depth products and basic information of AVH09C1 and WDC-SD.
(4) NDVI < NDVI_{\text{min}} (\text{veg})$: NDVI is a very sensitive indicator for detecting the transition between snow and vegetated areas. Pure snow pixels have a negative NDVI.

(5) R3 < R4_{\text{max}} (\text{snow})$: This is the most important test to distinguish between snow and water clouds. It is based on the fact that the reflectance of snow in the mid-infrared is much lower than that of clouds. It is very effective and stable.

(6) R1 > R1_{\text{min}} (\text{snow})$: This is the key snow test. It makes use of the large albedo between snow and other land covers including water in the visible channels of AVHRR.

However, the daily snow cover comparison results showed a great cloud contamination. In order to weaken the cloud impact, we used the neighbourhood merge method. With this processing each daily snow cover result was combined with the data from the previous and next periods. If the cloudy pixels are both ‘snow’ in the two neighbouring data, the pixel is finally determined as ‘snow’. Specific process is presented in the chart (Figure 3). Furthermore, the snow depth product of WDC-SD was used to extract features under cloud and gives snow depth information of every pixel. WDC-SD was first re-sampled to 0.05° using the nearest neighbour interpolation (Liang et al. 2008; Deng et al. 2015). If the WDC-SD value is 0, the corresponding cloud pixel is classified as land, and if higher than 0, the corresponding pixel will be regarded as snow with its snow depth value. The detailed composition rules are indicated in Figure 3.

5. Validation with station data

In this study, we use station data of the year 1998 to validate the spatial patterns of the snow depth mapping results (LTDR–WDC-SD) produced from the LTDR and WDC-SD. Ground snow occurrence recorded at 71 meteorological stations operated by the China Meteorological Administration was used to evaluate the accuracy of the snow depth image.

The experiment is to estimate the effects of the image fusion between LTDR and WDC-SD. Figure 4 shows the accuracy (classification agreement, commission error, omission error, correlation and standard error) of snow cover classification when using WDC-SD data alone and merged LTDR–WDC-SD data. When using WDC-SD alone, the correlation coefficient between retrieved and measured snow depth is lower than that of LTDR–WDC-SD, with a value of 0.69; the standard error of LTDR–WDC-SD is 0.04122, which is also better than that of WDC-SD, indicating the classification using merged data-set gives a higher accuracy than using WDC-SD alone. In fact, the

Figure 3. Image ‘a’ is snow cover extending map AVH09C1_snow derived from AVHRR-LTDR. Image ‘b’ is the result of neighbourhood method. Image ‘c’ is final result after the composition of snow cover data and PM data. Table is the composition rules of the neighbourhood method. Table α is the composition rules of snow cover data and PM data. Sample date: 01/03/1998 and compositing rules of the two steps.
correlation reflects a non-ideal linear relationship which may be due to the gap in spatial resolution. It should be pointed out that the spatial resolution of the WDC-SD is about 25 km and thus the derived snow cover product has a relatively high heterogeneity.

Moreover, the comparison between Figure 4(a, b) reveals that the proposed method (LTDR–WDC-SD) using both BT and SR has substantially solved the underestimation problem which existed when using BT alone. The following analyses allow us to evaluate the temporal and spatial accuracy of the proposed method.

From Figure 4, it can also be found that the LTDR–WDC-SD classification algorithm correctly identified the snow class at all stations in 83.5% of the cases and that of WDC-SD is only 69.1%, indicating that the merged data can improve the snow cover mapping. Commission error of LTDR–WDC-SD is much lower than that of WDC-SD while the omission error is slightly higher. In all the 5130 samples used for validation, 1305 non-snow samples are mis-identified as snow for WDC-SD, while the number reduces to 469 for LTDR–WDC-SD, revealing our products largely improve the non-snow region extraction. Although LTDR–WDC-SD mis-identified 89 snow samples more than WDC-SD, the whole accuracy of using LTDR–WDC-SD is much improved. However, it should be noted, because of the very low spatial resolution of PM data, the accuracy of snow depth extraction remains to be improved according to previous studies (Chang et al. 1987; Che et al. 2008). Nevertheless, since currently PM data is the only data that can provide snow

Figure 4. Validation of LTDR-WDC-SD/WDC-SD by meteorological stations; success stands for classification agreement of snow cover; confusion matrix of the two data including commission and omission of the two products.
depth information for a long term, more advanced data with higher spatial resolution can be expected in future.

6. Spatial–temporal variation of annual snow disasters

To get further snow disaster information for the past 30 years, we classified the snow disasters into four levels (snow disaster level, SDL): light, moderate, severe and extremely severe. The snow depth and lasting days are determining factors for SDL classification. Even if a strong snowfall did not lead to any economic loss or livestock death, it would also be regarded as potential threats. Therefore, only if snow depth or lasting days follow the classification rules, it will be regarded as disaster. The rules are from China Meteorological Disaster Code (Figure 5) (Zi 2007; Liu 2008).

Daily snow depth product: LTDR–WDC-SD was used to extract snow patterns. For instance, only when snow depth is between 2 and 5 cm and lasting days is between 11 and 20 (Figure 5) can it be identified as SDL-1. The account of each level that happened in one year is also calculated.

According to 31-year SDL statistical data (Figure 6), the annual variation of SDL-1 and SDL-2 is minor, while that of SDL-3 and SDL-4 sharply fluctuates. In 1983, 1985, 1997, 1998 and 2008, there were abnormal changes in SDL-4 area. In 1998, the area of SDL-4 reaches the crest value. Only area of SDL-2 shows a significant decreasing trend with the $R$-square reaching 0.4, while the area of other levels presents insignificantly decreased trend. At the same time, the annual variation of SDL-4 has the largest fluctuation (standard deviation $\sigma$ = 5.06). The extremely severe snow disasters not only cause largest damage but vary greatly at annual scales.

Referring to Chinese official historical records, in 1983, Changdu county of Tibet suffered extremely severe disaster in March. In 1985, both Dingqing and Changdu suffered extremely severe snow disaster, leading to death of more than 43,000 livestock. In 1997 and 1998, more than 820,000 livestock were dead and 100,000 people’s lives were affected due to the extremely severe disaster which is the largest loss in the past 30 years. As mentioned in the Section 1, a heavy snow disaster occurred in Maduo, Qinghai Province. Furthermore, with the annual spatial pattern showed in Figure 7, it is possible to get more detailed spatial-temporal characteristics for snow disaster occurrence in the TP.

In 1983, part of Eastern Tibet and Southern Qinghai suffered extremely severe snow disasters. In 1985, a large area of Northern Tangula Mountains suffered extremely severe snow disaster, where even light snow disasters did not occur for some other years (e.g. 1988, 1989, 1993, 2001, 2011). In

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Four snow disaster levels recognized by snow depth (SD/cm) and lasting days (LD/day): (1) green stands for level 1: light; (2) yellow stands for level 2: moderate; (3) orange stands for level 3: severe; (4) red stands for level 4: extremely severe. (To view this figure in colour, see the online version of the journal.)
1998, almost all the inland TP suffered extremely severe snow disasters. In 2008, the extent of extremely severe disaster occurrence is apparently smaller than those of 1985, 1997 and 1998, and only just a few happened in Eastern TP. In addition to these areas, other regions show a stable status in annual snow disaster occurrence. For example, part of Northern Kunlun Mountains suffered light-to-moderate snow disasters in long time series and some areas around Nyainqentanglha and Hengduan Mountains regularly suffered extremely severe snow disasters. In Eastern Gandise Mountain, almost no snow disaster happened in this area in 31 years.

In previous studies, Zhou concludes that snow disasters became especially severe after 1990, and in this study, during 1990–1998, there was a clearly increasing trend especially for the annual area of SDL 44. But after 1999, the area shrunk to a very low level and most areas become equable, even if it expanded a little in 2008, it is still not comparable with those in 1983, 1985, 1997 and 1998. Furthermore, the annual variation trend of SDL 4 can be easily linked with El Niño meteorological abnormality, as 1983 and 1998 are El Niño years. Ren et al. (2016) indicated that snow depth anomalies were typically associated with El Niño in their study in the TP. In spite of this phenomenon, we cannot draw a conclusion that El Niño will lead to great snow disasters in the TP, due to the too few samples. As the El Niño comes again in 2015 and 2016, the snowfall in the TP should be paid more attention.

7. The frequency of each level for past 30 years in county scale

With 31 years’ SDL data-set, each level frequency is able to be calculated in pixel scale. Since snow disaster assessment is closely associated with the government policy, the administrative unit (in terms of county) was incorporated into the spatial evaluation and comparison of snow disasters.

For light and moderate snow disasters (SDL 1 and 2), they happened in almost all regions of the TP except the Southern Kailas area. For severe and extremely severe disasters (SDL 3 and 4), the frequency is much higher in the middle-east of the TP.
Compared to Eastern China, the population of the TP is much lower; here we selected 25 counties (population > 50,000 in Tibet, population > 100,000 in Qinghai) to assess the disasters’ frequency and area for the past 31 years (Table 1). From this table, we find all the counties have suffered light-to-moderate snow disasters, Hui Autonomous County of Menyuan (HACM), Datong Hui and Tu Autonomous County (DHTAC), Tu Autonomous County of Huzhu (TACH), Changdu, Jomda and Mangkan suffered over 10 light snow disasters and HACM, Changdu, Jomba and Banbar suffered over 10 moderate snow disasters. Deengqeen, Biru and Banbar suffered over 10 severe snow disasters, and Xigazee, HACH, Minhe Hui and Tu Autonomous County (MHTAC), Xining and Ledu have not suffered severe snow disasters during the 31 years. As for Lhasa and Gonghe, the disaster-affected area is so small that it can be ignored. For extremely severe snow disasters, Banbar, Nagqu, Biru, Deengqeen and MHAC suffered at least five times with affected area over 70%. Eleven counties with over 30% population have not suffered severe snow disasters which is consistent with the historical records. However, there are also some counties with relatively large population suffering severe and extremely severe snow disasters for the past 31 years. For example, North-eastern
Changdu has suffered extremely severe snow disasters, and only North Nagqu can be assumed 'safe' from SDL 3 and SDL 4 snow disasters. With the quantitative spatial-temporal pattern showed in Table 1 and Figure 8, the snow risk could be predicted to serve the husbandry development and urban and rural planning for governmental policy-making.

8. Conclusion

The objective of this study is to analyze spatial-temporal characteristics of snow disasters from 31 years’ snow depth products derived from LTDR and PM data. The classification algorithm is based on sequential hierarchical thresholds in order to map snow from the AVHRR images. They were established empirically and thus specific to the TP conditions. The snow depth products were validated using station data and the classification results were demonstrated to be improved compared to the original snow depth products. These daily snow depth products were classified to four-level snow disaster data from 1982 to 2012 to explore the temporal and spatial characteristics of snow disasters in different levels. The result indicated that (1) in 1983, 1985, 1997, 1998 and 2008, large areas suffered extremely severe snow disasters. The annual variation of light and moderate snow disaster areas is less than that of severe and extremely severe areas. After 1999, the annual area of extremely severe is more stable and small than before. (2) Some areas suffered severe snow disasters in 1985, 1997 and 1998, while in other years they remain undisturbed. Part of the middle-east TP suffered extremely severe snow disaster almost every year. (3) Some counties with larger population never suffer severe or extremely severe snow disasters, while some other counties suffered more severe snow disasters in the past 31 years.

| County         | L1-area (%) | L1-mean (times) | L2-area | L2-mean | L3-area | L3-mean | L4-area | L4-mean | Population (10^3) |
|----------------|-------------|-----------------|---------|---------|---------|---------|---------|---------|-------------------|
| HACM           | 89.87       | 20              | 98.24   | 10      | 99.12   | 8       | 71.81   | 5       | 141               |
| Golmud         | 78.00       | 8               | 60.75   | 7       | 45.92   | 7       | 28.81   | 3       | 136               |
| DHTAC          | 100.00      | 17              | 99.18   | 6       | 98.36   | 4       | 28.69   | 2       | 416               |
| TACH           | 82.71       | 13              | 82.71   | 3       | 63.16   | 2       | 11.28   | 1       | 357               |
| Gonghe         | 46.39       | 4               | 29.16   | 4       | 12.52   | 4       | 7.51    | 3       | 112               |
| Huangzhong     | 100.00      | 6               | 93.68   | 3       | 29.47   | 1       | 22.11   | 1       | 448               |
| Huangyuan      | 90.00       | 5               | 98.33   | 3       | 66.67   | 2       | N       | N       | 129               |
| Ledu           | 77.88       | 3               | 19.23   | 2       | N       | N       | N       | N       | 262               |
| Xining         | 83.33       | 3               | 100.00  | 1       | N       | N       | N       | N       | 1849              |
| MHTAC          | 24.36       | 3               | 2.56    | 1       | N       | N       | N       | N       | 346               |
| HACH           | 81.58       | 3               | 16.67   | 1       | N       | N       | N       | N       | 213               |
| SACX           | 85.71       | 5               | 50.00   | 3       | 10.00   | 1       | N       | N       | 104               |
| Deengqeen      | 11.68       | 3               | 29.67   | 4       | 75.70   | 11      | 88.79   | 10      | 55                |
| Changdu        | 96.06       | 17              | 99.64   | 11      | 72.40   | 7       | 100.00  | 2       | 90                |
| Jomda          | 100.00      | 19              | 98.97   | 10      | 99.49   | 3       | 32.31   | 2       | 80                |
| Biru           | 51.72       | 8               | 80.23   | 8       | 94.02   | 11      | 95.63   | 8       | 60                |
| Nagqu          | 97.06       | 9               | 97.88   | 8       | 95.43   | 7       | 79.45   | 6       | 90                |
| Banbar         | 22.55       | 5               | 50.45   | 10      | 82.49   | 14      | 93.77   | 7       | 60                |
| Lhunzhub       | 90.36       | 7               | 71.69   | 7       | 46.39   | 4       | 22.89   | 4       | 70                |
| Mangkam        | 95.79       | 11              | 95.44   | 4       | 32.98   | 3       | N       | N       | 76                |
| Namling        | 77.74       | 7               | 73.42   | 4       | 61.79   | 3       | 28.24   | 2       | 70                |
| Doilungdeeqeen | 93.20       | 3               | 46.60   | 2       | 28.16   | 1       | N       | N       | 55                |
| Lhasa          | 76.19       | 3               | 23.81   | 2       | 9.52    | 2       | N       | N       | 559               |
| (chengguan)    |             |                 |         |         |         |         |         |         |                   |
| Xigaze         | 8.70        | 2               | 4.35    | 2       | N       | N       | N       | N       | 90                |
| Needong        | 71.43       | 5               | 52.38   | 2       | 27.38   | 2       | N       | N       | 100               |

HACM, Hui Autonomous County of Menyuan; DHTAC, Datong Hui and Tu Autonomous County; TACH, Tu Autonomous County of Huzhu; MHTAC, Minhe Hui and Tu Autonomous County; HACH, Hui Autonomous County of Hualong; SACX, Salar Autonomous County of Xunhua.
Figure 8. Frequency of each level for 31 years. The pixel value is the disaster times happened in 31 years and the shape file is administrative divisions.
Acknowledgments

The researchers would like to thank the National Library of China for providing historical records.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study is supported by the Special Fund for Ecological Assessment of the Three Gorges Project [0001792015CB5005]; Forest Scientific Research in the Public Welfare [grant number 201504323]; National High Technology Research and Development Program of China (863 Program) [grant number 2013AA12A302].

ORCID

Hang Yin http://orcid.org/0000-0003-3412-0345
Chunxiang Cao http://orcid.org/0000-0002-4007-1546
Min Xu http://orcid.org/0000-0002-6154-9676
Wei Chen http://orcid.org/0000-0003-0303-3978
Xiliang Ni http://orcid.org/0000-0001-5957-9721
Xuejuan Chen http://orcid.org/0000-0001-5957-9721

References

Chang ATC, Foster JL, Hall DK. 1987. Nimbus-7 SMMR derived global snow cover parameters. Ann Glaciol. 9:39–44.
Che T, Li X, Jin R, Armstrong R, Zhang T. 2008. Snow depth derived from passive microwave remote-sensing data in China. Ann Glaciol. 49:145–154.
Dai L, Che T, Wang J, Zhang P. 2012. 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.
Deng J, Huang X, Feng Q, Ma X, Liang T. 2015. Toward improved daily cloud-free fractional snow cover mapping with multi-source remote sensing data in China. Remote Sens. 7:6986–7006.
Dong A, Ju Z, Xin X, Zhou L. 2001. The singular spectrum analysis of snow damage in Eastern Qinghai-Xizang Plateau. Plateau Meteorol. 20:214–214.
Dressler K, Leavesley G, Bales R, Fassnacht S. 2006. Evaluation of gridded snow water equivalent and satellite snow cover products for mountain basins in a hydrologic model. Hydrol Process. 20:673–688.
Gong G, Cohen J, Entekhabi D, Ge Y. 2007. Hemispheric-scale climate response to Northern Eurasia land surface characteristics and snow anomalies. Global Planet Change. 56:359–370.
Hall DK, Riggs GA, Salomonson VV, DiGirolamo NE, Bayr KJ. 2002. MODIS snow-cover products. Remote Sens Environ. 83:181–194.
Liang TG, Huang XD, Wu CX, Liu XY, Li WL, Guo ZG, Ren JZ. 2008. An application of MODIS data to snow cover monitoring in a pastoral area: a case study in Northern Xinjiang, China. Remote Sens Environ. 112:1514–1526.
Liang T, Liu X, Wu C, Guo Z, Huang X. 2007. An evaluation approach for snow disasters in the pastoral areas of northern Xinjiang, PR China. NZ J Agric Res. 50:369–380.
Liu G. 2008. Meteorological disaster code of China:Tibet. Beijing: Meteorological Press.
Pu Z, Xu L, Salomonson VV. 2007. MODIS/Terra observed seasonal variations of snow cover over the Tibetan Plateau. Geophys Res Lett. 34.
Qobilov TFP, Vasilina L, Baumgartner MF. 2001. Operational technology for snow-cover mapping in the Central Asian mountains using NOAA-AVHRR data. IAHS-AISH Publ. 267:76–80.
Ren HC, Li W, Ren HL, Zuo J. 2016. Distinct linkage between winter Tibetan Plateau snow depth and early summer Philippine Sea anomalous anticyclone. Atmos Sci Lett. 17:223–229.
Simpson JJ, Stitt JR, Sienko M. 1998. Improved estimates of the areal extent of snow cover from AVHRR data. J Hydrol. 204:1–23.
Welch RMNR, Navar MS, Sengupta SK, Goruch AK, Rabindra P. 1992. Polar cloud and surface classification using AVHRR imagery: an intercomparison of methods. J Appl Meteorol. 31:405–420.
Zhang Y, Li B, Zheng D. 2002. A discussion on the boundary and area of the Tibetan Plateau in China. Geographical Res. 21:1–8.
Zhou L, Li H, Wang Q. 2000. The basic characteristics of heavy snowstorm process and snow disaster distribution in eastern pastoral areas of Qinghai-Xizang Plateau. Plateau Meteorol. 19:450–450.
Zi W. 2007. Meteorological disaster code of China:Tibet. Beijing: Meteorological Press.