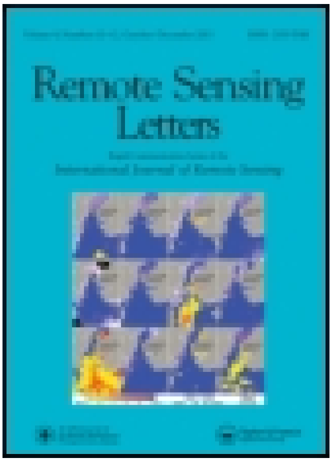
This article was downloaded by: [University of Connecticut]
On: 09 October 2014, At: 18:01
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Remote Sensing Letters
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/trsl20

Reliability of long-term snow depth data sets from remote sensing over the western arid zone of China

Qiming Zhou[a] & Bo Sun[a]

[a] Department of Geography and Centre for Geo-computation Studies, Hong Kong Baptist University, Kowloon, Hong Kong S.A.R., China

Published online: 25 Sep 2013.

To cite this article: Qiming Zhou & Bo Sun (2013) Reliability of long-term snow depth data sets from remote sensing over the western arid zone of China, Remote Sensing Letters, 4:11, 1039-1048, DOI: 10.1080/2150704X.2013.832841

To link to this article: http://dx.doi.org/10.1080/2150704X.2013.832841

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Remote Sensing Letters, 2013
Vol. 4, No. 11, 1039–1048, http://dx.doi.org/10.1080/2150704X.2013.832841

Reliability of long-term snow depth data sets from remote sensing over the western arid zone of China

QIMING ZHOU and BO SUN*
Department of Geography and Centre for Geo-computation Studies, Hong Kong Baptist University, Kowloon, Hong Kong S.A.R., China

(*Received 23 May 2013; accepted 4 August 2013*)

Due to the coarse spatial resolution of imagery and heterogeneity of snow physical parameters, the currently available snow depth data sets derived from passive microwave sensors have shown significant accuracy variations in different parts of the world. This study aims to analyse the reliability of existing remote sensing snow depth products for the arid zone of China. Two long-term products were compared and evaluated including the GlobSnow Snow Water Equivalent product ('the GlobSnow product') and the Long-term Snow Depth Dataset of China ('the WestDC product'). Nine-year ground measurements from 35 sampling sites with diverse topographical conditions were used as ground references for the accuracy assessment. Statistical analysis methods such as intra-class correlation coefficient and root mean square error (RMSE) were adopted for the consistency test and accuracy assessment. Analysis of variance (ANOVA) was employed to examine whether the data reliability varied by seasonal or locational factors. The results show that the two products in general do not agree well in the study region. However, the generalized data with different temporal resolutions tend to yield better results in terms of data consistency and accuracy. Compared to the GlobSnow product, the WestDC product has shown a better accuracy with the RMSE of 8.23, 7.43, and 6.56 cm for the original daily, and generalized weekly, and monthly data, respectively. According to the ANOVA test, season and latitude show statistically significant impacts on data reliability, while altitude and terrain complexity do not. Data reliability declines with higher latitude and it rapidly falls down to an unacceptable level in snow melting periods. This study provides a quantitative assessment on the quality of the snow depth products and raises the awareness of data consistency issues of these products for regional applications.

1. Introduction

Snow cover is increasingly recognized as a sensitive indicator of global climate change, especially in mountainous areas with less direct influence of human activities (Nogués-Bravo *et al*. 2007, Li *et al.* 2008). Among various parameters of snow cover, snow depth is considered vital, particularly for estimating the snow accumulation by snow volume. In the western arid zone of China, the snowmelt run-off is the major supply of water resources that is vital for lives in the harsh environment. The accurate and reliable snow depth data are therefore highly desirable not only for estimating the

---

*Corresponding author. Email: sun.bo@msn.com snowmelt run-off but also for evaluating the impacts of changing snow cover on the fragile ecosystem.

Passive microwave remote sensing technology has shown its capability of providing a large-extent and continuous observation of snow depth at all-weather conditions (Chang *et al.* 1987). To build an empirical model for snowmelt run-off estimation, a long-term time series data are needed. Given that the continuous global coverage dates back to 1978 by passive microwave sensors such as Scanning Multichannel Microwave Radiometer (SMMR) onboard the Nimbus-7, Special Sensor Microwave Imager (SSM/I) onboard the Defense Meteorological Satellite Program (DMSP) series platforms, and Advanced Microwave Scanning Radiometer for the Earth Observing System (EOS) (AMSR-E) onboard EOS Aqua, some long-term global/regional snow depth data sets have been produced and released based on the technology.

For the western arid zone of China, two long-term remote sensing snow products are readily available, including the GlobSnow Snow Water Equivalent (SWE) product ('the GlobSnow product') and the Long-term Snow Depth Dataset of China ('the WestDC product'). With a coarse spatial resolution (e.g. 25 km), these products aim to support studies at the global or international scales. The applicability of the products, however, has been questioned for local applications due to the uncertainties caused by physical and validation limits. The physical parameters of snow cover such as density and grain size might vary at different places. Errors caused by spatial heterogeneity of snow are difficult to avoid. Research works also pointed out that diverse underlying surface of snow cover, complex topography and wet snow would reduce the accuracy of snow depth detection (Chang *et al*. 1991, Dong *et al*. 2005). For validation, the limited availability of ground observation data make the calibration of the snow depth estimation results very weak by using only few weather stations and short period of time (Chang *et al*. 2005, Pulliainen 2006, Che *et al*. 2008, Luojus *et al*. 2010).

Because of the above uncertainties, this study aims to evaluate the reliability of the two remote sensing products for the western arid zone of China. Accuracies of selected available snow depth data sets are assessed based on multiple years of ground measurements from all available weather stations. In order to verify seasonal and locational effects on the data reliability, the impacts of wet snow and geographical location are also investigated.

2. Methodology

This study is based on the analysis of point data. Pairs of snow depth estimates from the two remote sensing products were sampled according to the locations of weather stations. Accordingly, ground measurements for the sampling sites were collected as ground reference data. Statistical methods such as intra-class correlation coefficient (ICC) and root mean square error (RMSE) were adopted for evaluating data reliability including consistency and accuracy. In order to present the differences of data reliability in respect to time and space, the sample data were categorized and analysed by season and geographical parameters such as latitude, altitude, and terrain complexity.

2.1 *Study area*

This study was conducted in Xinjiang Uygur Autonomous Region of China (figure 1). Xinjiang, covering an area of 1.66 million km^2, is regarded as one of the most important snow cover regions in China. Situated in the hinterland of the Eurasian continent,

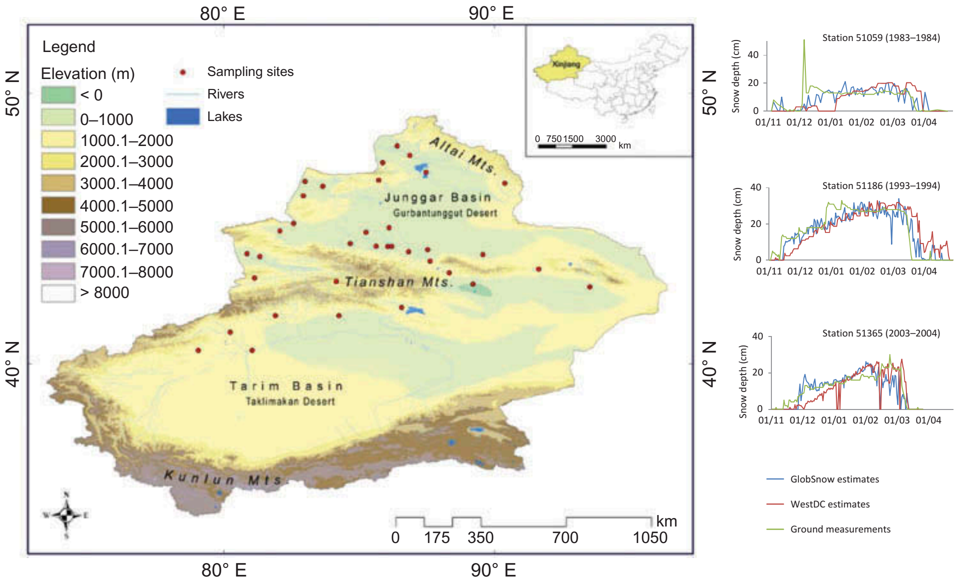


Figure 1. Study area with the description of topography and the locations of sampling sites with some examples of data.

this region has a typical continental climate with very low average annual precipitation of 146 mm (Jiang and Dou 2001). The topography of this region is characterized as three parallel mountain ranges with two basins lying between them. The Tianshan Mountains extending from east to west and divides the whole region into two parts: the North and South Xinjiang. As the high mountains blocks water vapour, the snowfalls are mainly at the North Xinjiang and some parts of the Kunlun Mountains in the south. Given that the region is located in an extremely dry arid zone, the alpine snow cover is the most important water resource for lives.

2.2 *Remote sensing data sets and data pre-processing*

In this study we selected two remote sensing products for evaluation, namely, the GlobSnow (version 1.3; Finnish Meteorological Institute (FMI), Helsinki, Finland) and the WestDC products. The former was issued by the Finish Meteorological Institute (FMI), as a part of the GlobSnow project supported by the European Space Agency (ESA). Snow depth estimates were derived by using an algorithm based on a semi-empirical snow emission model which combines brightness temperature difference between vertically polarized channels of 19 and 37 GHz and ground observation data (Pulliainen 2006). The depth values were then converted to SWE values by assuming a constant snow density of 0.24 g cm^{-3} regardless of location and season (Takala *et al*. 2011). Compared to independent ground reference data over the Russia, the accuracy of the product was reported with an RMSE of 43.2 mm for Eurasia and about 30–40 mm for restricted analysis to SWE values below 150 mm (Luojus *et al*. 2010, Takala *et al*. 2011). The latter was issued by the Environmental and Ecological Science Data Center for West China (WestDC). Snow depth estimates were derived by using a modified Chang's algorithm (Chang *et al*. 1987) to adapt into the environment in China (Che *et al*. 2008). Two channels with the same frequencies (i.e. 19 and

Table 1. The general properties of the snow depth products under the investigation.

	GlobSnow product (version 1.3)	WestDC product
Measurement	Snow water equivalent (mm)	Snow depth (cm)
Areal extent	North hemisphere (above latitude 35° N)[1]	China (60° E–140° E, 15° N–55° N)
Period	November 1979–December 2011	November 1978–December 2010
Temporal intervals	Daily, weekly, and monthly (average and maximum)	Daily
Projection	Equal Area Scalable Earth Grid (EASE-Grid) – north hemisphere	Latitude–longitude

Note: [1]Due to some physical reasons, a mountain mask is utilized, which means not all mountainous regions are included in the GlobSnow product.

37 GHz) but in a different polarization were employed for snow depth retrieval after distinguishing snow cover from rainfall, cold desert, and frozen ground (Che *et al*. 2008). Based on the records from limited meteorological stations in 1983/1984 and 1993, the accuracy of the product was evaluated in general with a standard deviation of 6 cm but the actual value varied according to the sensors (Che *et al*. 2008). Table 1 shows the general properties of the two products.

Given that some mountainous regions were excluded in the GlobSnow product, no test data were chosen from the missing regions so as to keep the results of accuracy assessment comparable. Test data sets were collected for 35 sampling sites (refer to figure 1). The locations of the samples were defined based on two criteria: (1) there was a ground observation station where the historical ground measurement could be acquired; and (2) snow depth estimates from both of the remote sensing products were available. To match the time series of the two products, the data acquired in the period of 1979–2010 were utilized. Considering seasonal effect on data reliability, the whole snow season covering the falling and melting periods should be taken into account. In this study, therefore, the time series from November to April of the next year were used.

For assessing time scale effects, the WestDC weekly and monthly data sets were derived. A seven-day moving average was applied to the WestDC daily data to generalize weekly data, in the same way that the GlobSnow weekly data were produced. The WestDC monthly data were calculated using the mean and maximum values of the generalized weekly data within a month.

Because the GlobSnow product provides the measurement of SWE rather than snow depth, to make the two data sets comparable, equation (1) was applied for converting the SWE values back to snow depth estimates (SD, cm), with the fixed snow density (0.24 g cm^{-3}) as adopted in the derivation of SWE estimates (Takala *et al*. 2011).

$$\mathrm{SD} = (\mathrm{SWE}) \times 0.1 \times \frac{\rho_{\mathrm{water}}}{\rho_{\mathrm{snow}}} \tag{1}$$

where SWE represents the SWE estimate in millimetres, and ρ_{water} and ρ_{snow} stand for the densities of water and snow, respectively.

2.3 *Reference data*

Ground measurements at the 35 sampling sites were acquired for data validation. For an individual assessment, none of them were involved in the creation of the two selected products. To assess the two products in different eras, three-year data for each decade were utilized, namely 1983–1986, 1992–1995, and 2002–2005. Daily ground measurement data was generalized to weekly and monthly data so as to match the temporal resolution of the test data sets.

A digital elevation model (DEM) with 90-metre spatial resolution (the Shuttle Radar Topography Mission (SRTM) v4.1) was utilized for the analysis of topographical effects. A terrain complexity index (TCI), which measures the variation of elevations within an area, was derived based on the DEM data. According to Wang and Lü (2009), the optimal analytic unit of TCI for Xinjiang is 2.56 km^2. In this study, the standard deviation of altitude was used for measuring relief amplitude in an area with the radius of 10 grid cells (approximately 2.54 km^2). To match the spatial resolution of remote sensing products (i.e. 25 km), the mean TCI in the coarse pixel was calculated. Considering that the accuracy of the SRTM DEM data is about ±10 m (refer to Farr *et al*. 2007), the sampling sites were classified into two terrain complexity classes, i.e. TCI < 10 m or TCI ≥ 10 m.

2.4 *Reliability analysis*

The ICC was employed to assess the conformity of the two remote sensing products. For repeated measurements on the same sample group, it indicates how alike the results given by different observers are (Shrout and Fleiss 1979, McGraw and Wong 1996). Different from Pearson correlation coefficient (r) which demands independent variables, the application of ICCs does not need the assumption of independence (Bland and Altman 1990). Given that the two products originated from the same data source and pairs of samples can be treated as two measurements on the same group of targets, the ICC is more suitable for this case.

The ICC is conceptualized as the ratio of between-group variance to the total variance. The calculation is defined by several forms (Shrout and Fleiss 1979, McGraw and Wong 1996). In this study, the ICC(C, 1) model (McGraw and Wong 1996) defined by equation (2) was employed, since the analytical results need to be applied to the whole study region beyond the samples.

$$\hat{\rho}_{\mathrm{ICC(C,1)}} = \frac{M_R - M_E}{M_R + (k-1)\,M_E} \tag{2}$$

where, $\hat{\rho}_{\mathrm{ICC(C,1)}}$ represents the ICC value calculated under the ICC(C, 1) model; M_R represents the mean square for pairs of estimates; M_E represents the residual mean square; and k represents the number of observations. In this study, two observations were made on a single case, so that $k = 2$.

The range of the ICC is (0, 1). A greater ICC represents better data consistency. According to Landis and Koch (1977), ICC > 0.4 is acceptable; ICC $= 0.6$ is the threshold for excellent consistency; and ICC > 0.8 shows a perfect consistency. In this study, to minimize the bias caused by non-snow cover measurements, we excluded the cases with paired remote sensing estimates being equal to zero from the ICC computation.

The RMSE was calculated to assess the accuracies of remote sensing products by using the following equation.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(D_i' - D_i\right)^2}{n}} \tag{3}$$

where D_i and D_i' denote the ground measurement and remote sensing estimate, respectively for the ith sample, and n is the number of samples (sample size).

Relative RMSE (RRMSE) was also calculated by dividing the RMSE by ground measurement to show the relative errors for different categories for the analyses of seasonal and spatial position effects.

The daily data sets were utilized for analysing the seasonal and locational effects. The ICC and RMSE by month were calculated to indicate the seasonal effect on data reliability. Accuracy assessment indices (i.e. RMSE and RRMSE) by site were calculated and then grouped based on latitude, altitude, and terrain complexity classes to show their differences in space. ANOVA was employed to test whether data accuracy statistically varied by location and geographical features. All statistical analyses were performed by using Statistical Package for the Social Sciences (SPSS) software (version 16; SPSS Inc., Chicago, IL, USA).

3. Results

3.1 *Consistency of two products and overall accuracies*

Table 2 shows the results of consistency test and accuracy assessment at different time scales. The daily data show a moderate consistency (ICC = 0.438), while the generalized weekly and monthly data are clearly more consistent. Both monthly average and maximum present an excellent consistency (ICC > 0.6). The data validation result also shows that the generalized data yield a better accuracy with lower RMSE, except for monthly maximum.

3.2 *Seasonal effect on data reliability*

Table 3 shows the variation of data consistency for different months. Since samples with the value of zero are excluded in consistency test, sample size of each month

Table 2. Data consistency and accuracy assessments for the two remote sensing products under different temporal resolutions.

		Daily	Weekly	Monthly (average)	Monthly (maximum)
Consistency test	Sample size	94,342	128,371	5243	5305
	ICC*	0.438	0.569	0.622	0.620
Data validation	Sample size	28,960	37,697	1250	1250
	RMSE (cm) (the GlobSnow product)	9.54	8.02	7.23	10.27
	RMSE (cm) (the WestDC product)	8.23	7.43	6.56	8.56

Note: $^*p < 0.05$, ICCs for single measures are adopted to match the form of ICC(C, 1).

Table 3. Data consistency of daily snow depth data sets by month (from 1979 to 2010).

	NOV	DEC	JAN	FEB	MAR	APR
Sample size	6953	17,925	23,902	21,897	17,969	5696
ICC*	0.165	0.249	0.353	0.407	0.425	0.037

Note: $^*p < 0.05$, ICCs for single measures are adopted.

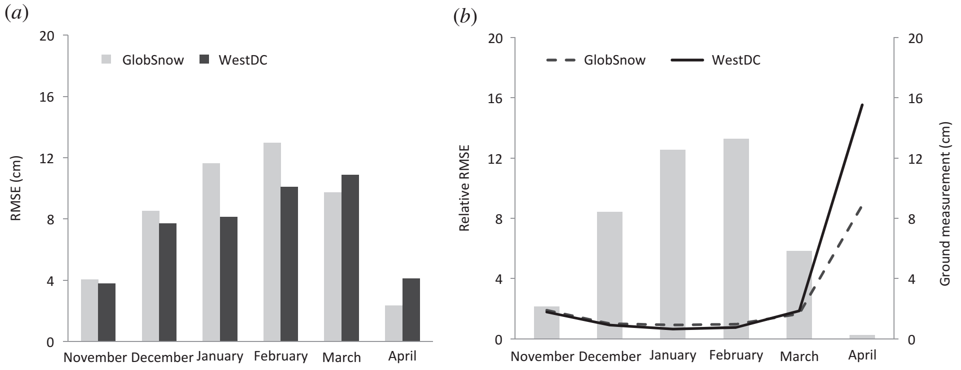


Figure 2. Accuracy assessments by RMSE (*a*) and relative RMSE (*b*) for different months.

implies the number of snow accumulation days. Accordingly, March is regarded as the last month of stable snow accumulation period while April is the start of snow melting period. The impact of snow melting on the reliability of remote sensing snow depth detection is obvious as the test data of March have shown a much better consistency than that of April. By comparing the ground measurement data, figure 2 illustrates absolute errors and relative errors as well for different months. From November to April, the RMSE varies from more than 13 to around 2 cm (figure 2(*a*)). The RRMSE also shows that the reliability of remote sensing estimates becomes very low in April compared with the ground measurements (figure 2(*b*)).

3.3 *Spatial position effects on data reliability*

According to the ANOVA results, the altitude and terrain complexity are not statistically significant factors that affect data accuracy at a 95% confidence level ($p = 0.892$ and 0.071 for the GlobSnow product and $p = 0.076$ and 0.623 for the WestDC product, respectively). The latitude, however, is significant ($p = 0.025$ for the GlobSnow product and $p < 0.001$ for the WestDC product, respectively). Figure 3

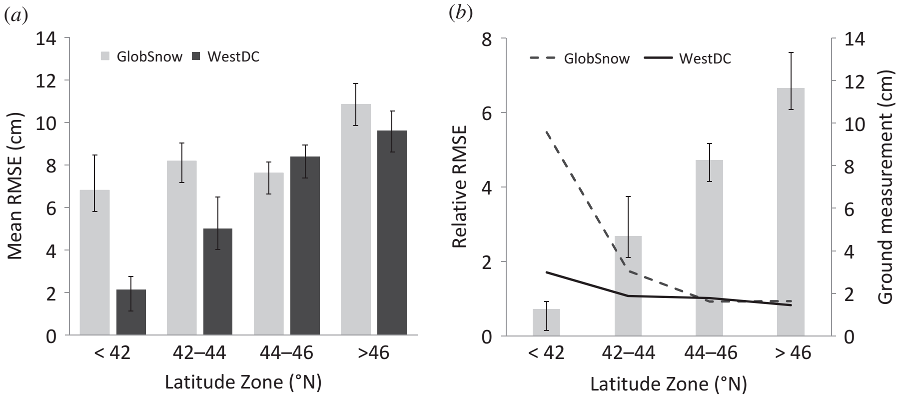


Figure 3. The mean RMSE with standard error of the mean (*a*) and relative RMSE (*b*) associated with monthly average of ground data for different latitude zones.

shows the mean RMSE and relative errors (RRMSE) for different latitude zones. The results suggest that data in high latitude regions yield a higher RMSE and the difference is more obvious in the WestDC than the GlobSnow product (figure 3(*a*)). Taking the ground reference data into account, the relative errors are similar for both the two data sets except for the region of 42° N below (figure 3(*b*)).

4. Discussion

Although originated from the same data source, remote sensing snow depth products do not correlate well. Furthermore, their accuracies are not high for the study area, which can be justified by the RMSE results. Some reasons for the low accuracy in our test might be (1) that the snow depth retrieval algorithms designed for global or country-level scales need to be further calibrated for the study area; (2) that the snow depth detected in the snow melting period gives low data reliability; and (3) that the spatial heterogeneity due to the coarse spatial resolution increases the uncertainty of the snow depth estimates. Comparatively, the WestDC product provides a better accuracy of snow depth estimate than the GlobSnow product, regardless of analytic temporal scales.

The seasonal effect is proven significant for data reliability. Since the snow depth retrieval algorithms normally assume dry snow, the quality of snow depth products is deteriorated during the snow melting period. For instance, our tests show that the ICC rapidly falls down to the unacceptable level in April, and the relative RMSE in April is also much lower than that in other months. Taking the WestDC product as an example, a scatter plot (figure 4) is presented to show the correlation between remote sensing estimates and ground measurements. Figures 4(*a*) and (*b*) show the correlations in January (representing the snow accumulation period) and in April (representing the snow melting period), respectively. Comparing these two figures, it is suggested that the agreements between remote sensing estimates and ground measurements varied greatly with the season, as the January data have shown a much closer agreement than that of April.

According to statistical analysis, the accuracy of remote sensing snow depth estimate is also highly related to latitude zone. The absolute errors increase from low to high latitude regions. However, the relative errors remain unchanged except for the

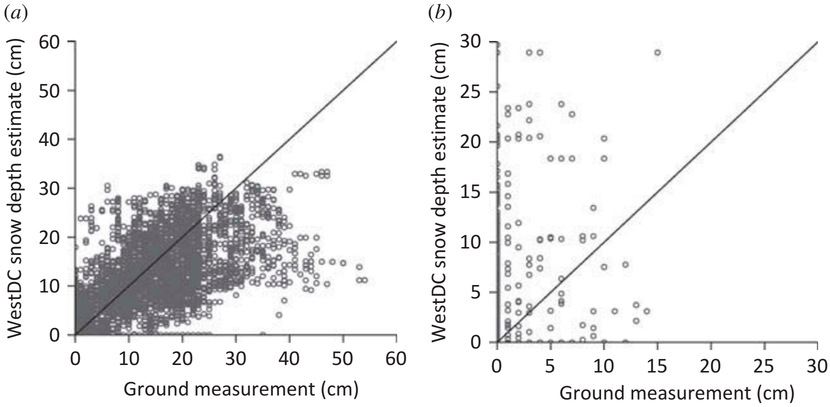


Figure 4. The scatter plots of the WestDC estimates against ground measurements: (*a*) in January, and (*b*) in April.

region of 42° N below. This implies that the absolute error increases as the thickness of snowpack increases within a certain range. Given that average snow depth in the region of 42° N below is lower than 1 cm, the large relative error confirms that passive microware is less reliable in detecting the depth of thin snow (Tait and Armstrong 1996, Armstrong and Brodzik 2002).

It is noted that the errors of the GlobSnow product reported in the study are less than in the letter of Takala *et al*. (2011). For one reason, the accuracy varies at different regions. Besides, Chang *et al*. (2005) indicated that more sites used in an accuracy assessment would yield a better result. It should be pointed out that possible 'value jumps' in the GlobSnow products (Hancock *et al*. 2013) may also cause uncertainties.

5. Conclusion

It is important to understand the reliability and applicability of remote sensing snow depth data sets for snow cover change studies. In this study, two readily available long-term products were compared and evaluated for the western arid zone of China. The results indicate that these two products do not correlate well for the study area, and their accuracies compared to the corresponding ground measurements are rather low. Comparatively, the WestDC product shows a better accuracy than the GlobSnow product. Seasonal factor and latitude have statistically significant effects on data reliability.

The results from this study suggest (1) that during the snow melting period remote sensing snow depth estimates become less trustworthy; and (2) that the data quality is appeared better at lower latitude than at higher latitude regions, excluding the measurements of thin snow. From the viewpoint of multi-temporal analysis, this study also suggests that generalized data at a coarser time scale can improve the data consistency and accuracy. It is therefore concluded that a more generalized temporal scale should be employed for a long-term time series analysis based on these existing remote sensing snow depth data sets. Further studies will aim to improve the data reliability by calibrating the remote sensing snow depth estimates with other reference data, such as higher resolution optical snow cover imagery and terrain parameters derived from DEMs.

Acknowledgements

This research is supported by the International Science and Technology Collaboration Project of China (2010DFA92720-24), the National Key Basic Research and Development Program Grant (2012CB719901), and the Hong Kong Baptist University Faculty Research Grant (FRG2/11-12/030). The Long-term Snow Depth Dataset of China is provided by Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn). The GlobSnow SWE product is provided by Finish Meteorological Institute (http://www.globsnow.info/swe/). The DEM data are provided by International Scientific and Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://datamirror.csdb.cn).

References

Armstrong, R.L. and Brodzik, M.J., 2002, Hemispheric-scale comparison and evaluation of passive microwave snow algorithms. *Annals of Glaciology*, **34**, pp. 38–44.

Bland, J.M. and Altman, D.G., 1990, A note on the use of the intraclass correlation coefficient in the evaluation of agreement between two methods of measurement. *Computers in Biology and Medicine*, **20**, pp. 337–340.

Chang, A.T.C., Foster, J.L. and Hall, D.K., 1987, Nimbus-7 SMMR derived global snow cover parameters. *Annals of Glaciology*, **9**, pp. 39–44.

Chang, A.T.C., Foster, J.L. and Rango, A., 1991, Utilization of surface cover composition to improve the microwave determination of snow water equivalent in a mountain basin. *International Journal of Remote Sensing*, **12**, pp. 2311–2319.

Chang, A.T.C., Kelly, R.E.J., Josberger, E.G., Armstrong, R.L., Foster, J.L. and Mognard, N.M., 2005, Analysis of ground-measured and passive-microwave-derived snow depth variations in midwinter across the Northern Great Plains. *Journal of Hydrometeorology*, **6**, pp. 20–33.

Che, T., Li, X., Jin, R., Armstrong, R. and Zhang, T., 2008, Snow depth derived from passive microwave remote-sensing data in China. *Annals of Glaciology*, **49**, pp. 145–154.

Dong, J.R., Walker, J.P. and Houser, P.R., 2005, Factors affecting remotely sensed snow water equivalent uncertainty. *Remote Sensing of Environment*, **97**, pp. 69–82.

Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D. and Alsdorf, D., 2007, The shuttle radar topography mission. *Reviews of Geophysics*, **45**, RG2004. doi:10.1029/2005RG000183.

Hancock, S., Baxter, R., Evans, J. and Huntley, B., 2013, Evaluating global snow water equivalent products for testing land surface models. *Remote Sensing of Environment*, **28**, pp. 107–117.

Jiang, Y. and Dou, Y. (Editors-in-chief), 2001, *The Provincial Atlas of China*, pp. 189–190 (Beijing: Star Map Press) (in Chinese).

Landis, J.R. and Koch, G.G., 1977, The measurement of observer agreement for categorical data. *Biometrics*, **33**, pp. 159–174.

Li, X., Cheng, G., Jin, H., Kang, E., Che, T., Jin, R., Wu, L., Nan, Z., Wang, J. and Shen, Y., 2008, Cryospheric change in China. *Global and Planetary Change*, **62**, pp. 210–218.

Luojus, K., Pulliainen, J., Takala, M., Lemmetyinen, J., Derksen, C. and Wang, L., 2010, *Global Snow Monitoring for Climate Research: Snow Water Equivalent (SWE) Product Guide*. European Space Agency Study Contract Report, ESRIN Contract 21703/08/I-EC. Available online at: http://www.globsnow.info/swe/GlobSnow_SWE_product_readme_v1.0a.pdf (accessed 22 May 2013).

McGraw, K.O. and Wong, S.P., 1996, Forming inferences about some intraclass correlations coefficients. *Psychological Methods*, **1**, pp. 30–46.

Nogués-Bravo, D., Araújo, M.B., Errea, M.P. and Martínez-Rica, J.P., 2007, Exposure of global mountain systems to climate warming during the 21st century. *Global Environmental Change*, **17**, pp. 420–428.

Pulliainen, J., 2006, Mapping of snow water equivalent and snow depth in boreal and sub-arctic zones by assimilating space-borne microwave radiometer data and ground-based observations. *Remote Sensing of Environment*, **101**, pp. 257–269.

Shrout, P.E. and Fleiss, J.L., 1979, Intraclass correlations: uses in assessing rater reliability. *Psychological Bulletin*, **86**, pp. 420–428.

Tait, A. and Armstrong, R., 1996, Evaluation of SMMR satellite-derived snow depth using ground-based measurements. *International Journal of Remote Sensing*, **17**, pp. 657–665.

Takala, M., Luojus, K., Pulliainen, J., Derksen, C., Lemmetyinen, J., Kärnä, J.-P., Koskinen, J. and Bojkov, B., 2011, Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer and ground-based measurements. *Remote Sensing of Environment*, **115**, pp. 3517–3529.

Wang, L. and Lü, X., 2009, Analysis of the relief amplitude in Xinjiang based on digital elevation model. *Science of Surveying and Mapping*, **34**, pp. 113–116 (in Chinese).