Journal of Hydrology 385 (2010) 23–35

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Toward advanced daily cloud-free snow cover and snow water equivalent products from Terra–Aqua MODIS and Aqua AMSR-E measurements

Yang Gao [a,b,c], Hongjie Xie [b,*], Ning Lu [b,d], Tandong Yao [c], Tiangang Liang [e]

[a] *Faculty of Earth Sciences, China University of Geosciences, Wuhan 430073, China*
[b] *Laboratory for Remote Sensing and Geoinformatics, University of Texas at San Antonio, San Antonio, TX 78249, USA*
[c] *Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, China*
[d] *Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China*
[e] *College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou 730020, China*

ARTICLE INFO

Article history:
Received 18 September 2009
Received in revised form 20 December 2009
Accepted 25 January 2010

This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Hervé Andrieu, Associate Editor

Keywords:
Snow cover
Snow water equivalent
Cloud-free
New daily products

SUMMARY

By taking advantage of the high spatial resolution of optical sensors and cloud penetration of a passive microwave sensor, a method is developed to generate new daily cloud-free snow cover (SC) and snow water equivalent (SWE) products, both in 500 m spatial resolution, utilizing daily Terra–Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) and Aqua Advanced Microwave Scanning Radiometer for NASA's Earth Observing System (AMSR-E) snow products. This method was tested in Fairbanks and Upper Susitna Valley, Alaska area for one hydrological year (October 2006–September 2007). The results confirm that daily MODIS products and Terra–Aqua MODIS combined products have similar and high classification accuracy (91–94%) in cloud-free conditions and that the daily combination can reduce cloud cover ∼10%. The results also show the snow accuracy of the new SC products is 86%, which is much higher than the 31%, 45%, and 49% of the Terra, Aqua, and Terra/Aqua combined snow cover products (in all weather conditions), respectively. The validation demonstrates that the accuracy of AMSR-E SWE products is 68.5% and they tend to overestimate SWE. Redistribution of SWE, based on sub-pixel analysis of AMSR-E pixels, not only generates the new product at higher spatial resolution, now more suitable for basin and regional monitoring and modeling, but also slightly increases the accuracy of the SWE estimations. This method can also be used in merging other optical data such as AVHRR, Landsat with passive microwave data such as SSMR, SSM/I, and for future NPP and NPOESS missions.

Introduction

Snow cover patterns have a significant impact on climate processes, surface hydrological cycles and ecological processes (Simpson et al., 1998; Simic et al., 2004). Frequent and long-term snow observation, accurate snow cover (SC) mapping and snow water equivalent (SWE) estimation are crucial for snowmelt-runoff prediction, operational flood control, water supply planning, and water resource management in basins where snowpack is a dominant water resource (Brown, 2000; Dressler et al., 2006). Conventional snow monitoring is mainly based on point measurements. However, sparse point observation networks cannot provide an overall picture on regional and global scales, due to their low spatial density or even absence in inaccessible regions (Derksen et al., 2005). Satellite images are readily available and provide spatio-temporal characteristics needed for snow monitoring. Since the middle of the 1960s, a number of satellite-derived snow products derived from visible and infrared imagery as well as from passive microwaves have been available, with a few recently available in near-real time through the Internet (Bitner et al., 2002).

Space-borne passive-microwave radiometers, such as Scanning Multichannel Microwave Radiometer (SMMR), Special Sensor Microwave/Imager (SSM/I), and Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E), can penetrate cloud to detect microwave energy emitted by snow and ice and provide information on snow water equivalent (SWE) or snow depth and thus estimate runoff (Wulder et al., 2007; Pulliainen, 2006). These passive microwave data are well suited to snow cover monitoring because of characteristics such as all weather imaging, large swath width with frequent overpass times, and relatively lengthy available time series (since 1970s) (Derksen et al., 2004). But the coarse spatial resolution (25 km of AMSR-E daily SWE product is the best available presently) hinders their applications in operational hydrological modeling and snow-caused disasters monitoring (Kelly et al., 2003; Dressler et al., 2006; Pulliainen, 2006). Optical sensors such as Advanced Very High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectraradiometer

* Corresponding author. Tel.: +1 210 458 5445; fax: +1 210 458 4469.
E-mail address: Hongjie.xie@utsa.edu (H. Xie).

0022-1694/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2010.01.022

(MODIS), Systeme Probatoire d'Observation dela Tarre (SPOT) and Landsat have been well developed to provide snow information with high spatial resolution (Salomonson and Appel, 2004; Dozier and Painter, 2004; Brown et al., 2007). But optical sensors cannot observe the earth surface when cloud, rainfall or darkness is present. It is difficult to find daily continuous images of cloud-free or cloud percentages lower than 10%, especially in snow seasons. High cloud obscuration becomes the major concern in utilizing snow products from optical sensors (Klein and Barnett, 2003; Zhou et al., 2005; Tekeli et al., 2005; Ault et al., 2006; Liang et al., 2008a,b; Wang et al., 2008, 2009; Xie et al., 2009; Parajka and Blöschl, 2008).

In order to overcome these problems, some methods were developed to improve snow retrievals by combining daily Terra–Aqua MODIS snow cover products or by blending MODIS and AMSR-E data. Since two independent MODIS snow cover retrievals from Terra and Aqua are shifted by a few hours and can be used in a complementary way, Xie et al. (2009) generate daily MODIS combined snow-cover maps, which decrease cloud cover by ~10% as compared with MODIS daily snow cover products MOD10A1 (Terra) or MYD10A1 (Aqua) alone and improved the snow classification accuracy in all weather conditions (51% against 44% of MOD10A1 and 34% of MYD10A1). But they still contain significant cloud cover. Snow information from passive microwave sensors such as AMSR-E was introduced to remove the cloud obscuration. Foster et al. (2007) presented their idea in developing a blended product to map global snow parameters, while the initial completed products was at a 25-km resolution and just included snow cover extent utilizing the information from global standard Aqua MODIS and AMSR-E data. Through visual comparison they found that the MODIS products have greater confidence for mapping snow cover extent than AMSR-E products and suggested that "when cloud-free MODIS observations are available, MODIS data will be used as 'truth'", and that "the microwave-derived snow cover will be used as 'truth' only in those areas where MODIS data is unavailable due to the presence of clouds and darkness". Over the Lower Great Lakes regions, Hall et al. (2007a) proved that this blended snow cover product provides more accurate determination of snow-covered area than is possible to obtain using either MODIS or AMSR-E data alone, in comparison with a snow-cover map developed using kriging to interpolate the station data. Liang et al. (2008b) produced new daily snow cover products at a 500-m resolution through combining snow cover information of Terra MODIS daily snow cover product (MOD10A1) and AMSR-E daily SWE product (AE_DySno). The combination removes cloud obscuration and significantly increases the snow classification accuracy to 75.4%. Although there is a significant increase (~42%) in snow agreement in respect to MOD10A1 in all-sky conditions, the accuracy is still ~23% less than MOD10A1 in clear-sky conditions, since the combination does bring some uncertainties.

The motivation of this study is to combine these two ideas. Prior to the merging of MODIS and AMSR-E snow information, the Terra and Aqua MODIS products are firstly combined. Since MODIS snow cover data in clear-sky conditions have high accuracy and high spatial resolution, we assume that the snow accuracy can be further improved as the cloud cover can be reduced first via Terra and Aqua MODIS combination, and therefore relative less coarse AMSR-E will be introduced. Furthermore, with better snow-cover maps, we should be able to redistribute the 25 km grid cell of AMSR-E SWE product into those snow-covered pixels only (500 m), thus advanced SWE maps with higher spatial resolution could be produced. One hydrological year's data (October 2006–September 2007) of Fairbanks and Upper Susitna Valley, Alaska area are used as a test to illustrate the improvement and validations of these new products.

Background

MODIS and its snow cover products

The MODIS instrument is a multi-spectral instrument with 36 bands and nominal spatial resolution of 250 m in two bands, 500 m in five bands, and 1 km in another twenty nine bands. It is operational on two Earth Observation System (EOS) spacecrafts, Terra (launched December 1999, overpassing the equator about 10:30 am) and Aqua (launched May 2002, overpassing the equator about 1:30 pm) (Hall and Riggs, 2007). Based on MODIS imagery, a suite of snow and ice products have been provided through the Distributed Active Archive Center (DAAC) of the National Snow and Ice Data Center (NSIDC) since September 2000. Daily snow cover product of MOD10A1 (Terra) or MYD10A1 (Aqua) is generated by selecting the observations acquired nearest nadir and having the greatest coverage of the grid cell from the many observations acquired during a day. It contains snow cover, snow albedo, fractional snow cover (Version 5 only), and quality assessment data in a compressed format of Hierarchical Data Format-Earth Observing System (HDF-EOS) along with corresponding metadata. The data consist of 1200 km by 1200 km tiles, with an actual 463.3 m spatial resolution in sinusoidal map projection. The MODIS snow cover image is a coded raster. Those coded integer values include 0 (sensor data missing), 1 (no decision), 11 (darkness, terminator or polar), 25 (land-no snow detected), 37 (inland water), 39 (ocean), 50 (cloud), 100 (snow-covered lake ice), 200 (snow), 254 (saturated MODIS sensor detector), and 255 (fill – no data expected for pixel) (Riggs et al., 2006).

AMSR-E and its daily SWE products

The AMSR-E instrument is a 12-channel, 6-frequency, conically-scanning, passive-microwave radiometer system, which is onboard the Aqua satellite (Lobl et al., 2002; Kawanishi et al., 2003). It measures horizontally and vertically polarized microwave radiation (brightness temperatures) ranging from 6.9 GHz to 89 GHz. Spatial resolutions of the individual measurements varies from 5.4 km at 89 GHz to 56 km at 6.9 GHz. It provides measurements of land, oceanic, and atmospheric parameters for the investigation of global water and energy cycles, including precipitation rate, sea surface temperature, sea ice concentration, snow water equivalent, soil moisture, surface wetness, wind speed, atmospheric cloud water, and water vapor (Kelly et al., 2003). The daily Level-3 SWE product (AE_DySno) has been available from the NSIDC DAAC since June 2002. This product is generated from AMSR-E/Aqua L2A Global Swath Spatially-Resampled Brightness Temperatures data. For each low frequency (<89 GHz) sample, snow depth retrieval is performed through snow maps masking and brightness temperatures classifying (Dewey and Heim, 1981). And then retrievals are calibrated and projected in the 25 km Equal-Area Scalable Earth Grids (EASE-Grids) array. The snow depth is finally converted to SWE storing in HDF-EOS format. Files contain core metadata, product-specific attributes, and 721 rows $\times$ 721 columns pixel data fields in 1-byte unsigned integer format. The pixel value for SWE include 0–240 (SWE values, the unit is mm), 248 (off-earth), 252 (land or snow impossible), 253 (ice sheet), 254 (water), 255 (data missing). Since actual SWE values were scaled down by a factor 2 for storing in the HDF-EOS file, thus for application, they must be scaled up by multiplying by 2 (Kelly et al., 2007).

Method

To produce daily cloud-free SC and SWE products at 500 m resolution, utilizing MODIS and AMSR-E products, we developed a