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Intra- and inter-annual variations in snow–water storage in data sparse desert–mountain regions assessed from remote sensing

Mir A. Matin [a], Charles P.-A. Bourque [a,b,c,*]

[a] Faculty of Forestry and Environmental Management, University of New Brunswick, 28 Dineen Drive, PO Box 4400, Fredericton, New Brunswick E3B 5A3, Canada
[b] Lanzhou Regional Climate Centre, Gansu Provincial Meteorological Bureau, Lanzhou 730020, Gansu, PR China
[c] The School of Soil and Water Conservation, Beijing Forestry University, 35 East Qinghua Road, Haidan District, Beijing 100083, PR China

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ABSTRACT

Seasonal water flow to semi-arid to arid lands worldwide is regularly controlled by precipitation and snowmelt processes in nearby mountain ranges, where few monitoring stations exist. In this paper we present a new approach to assess the seasonal and inter-annual development of precipitation and associated snow-cover area (SCA) and snow–water storage in the Qilian Mountains of NW China. The approach addresses the spatial enhancement and calibration of remote sensing (RS) data acquired from coarse-resolution TRMM (Tropical Rainfall Measuring Mission; ~26-km resolution) and MODIS images in the development of image-surfaces of in-mountain precipitation and surface air temperature at 250-m resolution for input to a new spatially-distributed monthly snow-accumulation and snowmelt model. Spatially-enhanced precipitation and air temperature surfaces were subsequently calibrated using either geographically-weighted regression or simple linear regression and point-data from climate stations. When point-extractions from the calibrated products were compared against a new set of independent climate-station data, their respective values were comparable, giving an overall r^2 of 0.87 for precipitation (RMSE = 10 mm month^{-1}) and 0.96 for surface air temperature. With input from calibrated surfaces, monthly SCA and snow–water equivalence (SWE) in the Qilian Mountains were subsequently modeled over a 10-year period (2000–2009). Seasonal values of SCA and SWE were compared with MODIS-based (optical) and AMSR-E passive microwave-based estimates of SCA and SWE. In most cases, comparisons revealed suitable agreement across the various evaluations of SCA. Minor discrepancy between MODIS- and AMSR-E-based estimates of SCA resulted in a mean overlap of 73% when modeled SCA was compared to MODIS-based SCA and 84% overlap, when compared to AMSR-E-based SCA. Modeled and AMSR-E-based estimates of SWE at lower- to upper-mountain elevations (≤3900 m above mean sea level; AMSL) compared fairly well. At elevations >3900 m AMSL, discrepancies between estimates were largely attributed to an overestimation of local precipitation.

1. Introduction

Assessing snow–water equivalence (SWE; i.e., the amount of water stored in snow) in the mountains is important in determining seasonal water flow in snowmelt-dominated river systems in mountainous watersheds. In these watersheds, snow accumulated in the mountains during the snow season is an important source of water to river networks downslope during late spring to mid-summer, when air temperatures in the mountains exceed the melting point of snow.

Measurements of snow depth, density, and SWE are usually not included in the standard data capture of most climate stations (Braun, 1991). Automated stations have been established to observe snowpack conditions at fine temporal resolutions (hourly to daily) in some parts of the world (e.g., SNOTEL; Fassnacht, Dressler, & Bales, 2003) and some manual measurements have been collected on project bases, but these measurements are usually very difficult to acquire and when acquired, they are usually not very representative of conditions beyond the area in which they were collected. Empirical studies in mountainous regions show very high standard deviations (60–100%) from mean snow cover as a result of the broad range of snow conditions encountered in mountainous environments (Fassnacht et al., 2003; Marchand & Killingtveit, 2005). Moreno, Latron, and Lehmann (2010) analyzed the accuracy of different interpolation methods in predicting snow distribution and found that the grid and sample size greatly affected model accuracy. They found that for a small catchment of 6 km^2, model accuracy diminished from 80% to 50% based on the D-index (Willmott, 1982), when sample locations were reduced from 991 to 100, suggesting that interpolation would fail to provide acceptable estimates of SWE for even larger unmonitored mountainous watersheds.

Optical RS has been previously used in the past to generate satisfactory calculations of snow-cover area (SCA; Braun, 1991) in the production of moderate to coarse resolution SWE distributions for input in hydrological models (Martinec, Seidel, Burkart, & Baumann, 1991). Recent

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* Corresponding author at: Faculty of Forestry and Environmental Management, University of New Brunswick, 28 Dineen Drive, PO Box 4400, Fredericton, New Brunswick E3B 5A3, Canada. Tel.: +1 506 453 4930; fax: +1 506 453 3538.
E-mail addresses: m.matin@unb.ca (M.A. Matin), cbourque@unb.ca (C.P.-A. Bourque).

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introduction of the Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) sensors have improved our capabilities to map SCA and SWE for regional and global applications (Kuchment, Romanov, Gelfan, & Demidov, 2010). However, sensor resolution and accuracy has caused some problems with the detection of snow, particularly when snow cover is shallow and discontinuous.

Accurate determination of spatiotemporal patterns in precipitation and surface air temperature is basic to modeling SCA and SWE. Historically, spatially-distributed estimates of precipitation and temperature were acquired by interpolating climate-station observations. Inherent in this approach is the assumption that precipitation and surface air temperature at locations not directly measured are adequately represented by values from surrounding monitoring stations. As a general rule, interpolation is recommended for areas where the number of climate stations is high with respect to target spatial resolution and application scale; whereas, spatial enhancement (statistical downscaling) of remote sensing (RS)-based products is recommended for areas where climate stations are sparse and landform is particularly complex (Lanza, Ramirez, & Todini, 2001).

RS-based assessments of precipitation, unlike assessments of land surface temperature, are usually indirect and are mostly modeled from remote measurements of related variables. Accuracy of RS-based estimates of instantaneous precipitation, thus far has generally been low, but reasonable estimates have been generated at longer timescales (Fiorucci, La Barbera, Lanza, & Minciardi, 2001; Hu, Yang, Wang, & Yang, 2013). For example, Ebert and Manton (1998) compared the results of the evaluation of 50 precipitation algorithms with precipitation data acquired with Doppler radar and concluded that satellite-based estimates of precipitation corresponded reasonably well at monthly timescales, with coefficients of correlation of 0.86–0.90 for geostationary satellites and 0.69–0.86 for AVHRR and SSM/I sensors. Lower accuracies were reported for instantaneous precipitation measurements with coefficients of correlation of 0.43–0.58 and 0.6–0.78 for geostationary satellites and AVHRR or SSM/I sensors, respectively. Tropical Rainfall Measuring Mission (TRMM; i.e., product 3B43), available at $0.25^\circ \times 0.25^\circ$ spatial resolution (~26 km × ~26 km), provides one of the best possible satellite-based product of total precipitation at broad temporal scales (e.g., monthly or annually; GCMD, 2010; Huffman et al., 1997, 2007). Validation of TRMM-precipitation for major climatic regions of Africa has shown that the 3B43-data closely matched raingauge data, with r^2-values (coefficients of determination) of 0.84–0.97 and normalized root mean squared error (RMSE) <50% for all regions, except for the arid-lands of northern Africa (Adeyewa & Nakamura, 2003). In another validation exercise (Fleming, Awange, Kuhn, & Featherstone, 2011), 3B43-precipitation data from Australia was compared with gridded monthly data generated from raingauge observations and found strong agreement between the two datasets, with coefficient of correlation of 0.93 ($r^2 = 0.86$).

An important limitation of TRMM-image data resides in the data's coarse spatial resolution. On account of the data's resolution, unrefined TRMM-data are usually not recommended for regional application. Spatial enhancement of TRMM-image products at scales appropriate for regional application is the subject of active research, mostly centered on the usage of a coarse relationship between normalized difference vegetation index (NDVI) and precipitation (Duan & Bastiaanssen, 2013; Immerzeel, Rutten, & Droogers, 2009; Jia, Zhu, Lu, & Yan, 2011). Although the relationship is useful at broader timescales (e.g., annually), the relationship fails to capture a significant portion of the variability at shorter time intervals, including at monthly timesteps (Duan & Bastiaanssen, 2013; Verlinde, 2011). Duan and Bastiaanssen (2013) proposed the generation of 1-km resolution monthly precipitation product from TRMM by initially enhancing the original TRMM-images with a NDVI-to-TRMM-precipitation-type relationship at an annual level and disaggregating annual values into monthly estimates based on proportions derived from the original TRMM-image series.

The research described here is motivated by the need to further investigate the eco-hydrometeorological processes involved in the long term self-support of desert oases in NW China. In earlier studies (e.g., Bourque & Hassan, 2009; Bourque & Mir, 2012; Zhang, Bourque, Sun, & Hassan, 2010), precipitation was calculated spatially with Genetic Algorithms trained on 10-years of monthly climate-station data and an assumed point-trend in upper-mountain precipitation. In general, the method reproduced monthly recorded precipitation at lower elevations (i.e., ≤3400 m above mean sea level, AMSL) reasonably well ($r^2 \geq 0.75$; Bourque & Hassan, 2009; Zhang et al., 2010). Greatest discrepancies between monthly values (modeled and recorded) normally occurred in the dry, lowlands of the Shiyang River watershed in the Hexi Corridor of westcentral Gansu ($r^2 = 0.75$), where local precipitation was observed to be lower (~115 mm yr^{-1}) and generally more intermittent because of its convective origin (Bourque & Hassan, 2009; Zhang et al., 2010). With further analysis of generated precipitation surfaces, it was determined that the quantities of precipitation calculated in the mountains may have been too high and, as a result, may have caused snow accumulation and associated calculations of SWE in the mountains to have been overestimated (Bourque & Mir, 2012; their Fig. 6). There is an anticipation that improved estimates of precipitation at a finer spatial resolution may help ameliorate computations of SWE in the mountains.

The specific objectives of this paper are to: (i) develop a new monthly snow accumulation and snowmelt model ("snowmelt model", hereafter) that addresses the melting of snow as a function of melting degree-days (utilizing surface air temperature; Dou, Chen, Bao, & Li, 2011; Li & Williams, 2008; Martinec & Rango, 1986; Wang & Li, 2001) and precipitation inputs based on spatially-enhanced MODIS-temperature and TRMM images; (ii) apply the snowmelt model to calculate SCA and SWE in the Qilian Mountains (NW China) from a decade of monthly data (2000–2009); and (iii) compare modeled outputs of SCA and SWE with their counterparts derived from MODIS and AMSR-E image-products in an analysis of intra- and inter-annual variation in SCA and SWE.

2. Study area

The study area comprises of the Shiyang and Hei River watersheds in westcentral Gansu Province, NW China (Fig. 1). The Shiyang River originates from the Qilian Mountains and flows northeastward before terminating in the Minqin-lake district (Li, Xiao, He, Chen, & Song, 2007). The watershed area is ≈49,500 km^2. Elevation in the Shiyang River watershed varies from 1284 to 5161 m AMSL, with an average elevation of 1871 m AMSL. The Hei River watershed, covering ≈128,000 km^2, is the second largest inland watershed in NW China (Gu, Li, & Huang, 2008). It includes the Zhangye sub-watershed covering ≈31,100 km^2. Elevation in the Zhangye sub-watershed varies from 1287 to 5045 m AMSL, with an average elevation of 2679 m AMSL (Fig. 1).

The study area comprises of four distinct ecoregions (Olson et al., 2001). Firstly, the Alashan Plateau desert in the north is noted for its extreme aridity, including portion of the Badain Jaran and Tengger deserts. Salt-tolerant, xerophytic shrub species, i.e., saxaul (*Haloxylon ammodendron*) and *Reaumuria soongolica* (Carpenter, 2001a) are common vegetation. Secondly, the oases in the southwestern portion of the Alashan Plateau; Liangzhou, at the south, and Minqin, at the north, are two important oases of the Shiyang River watershed (Li et al., 2007). Zhangye is the main oasis in the Zhangye sub-watershed. Spring wheat is the main food crop grown in the oases, which is usually supported by irrigation (Zhao, Nan, & Cheng, 2005). Thirdly, the montane grassland-meadows (at elevations ≤3300 m AMSL) and deciduous shrubland (elevations > 3300 m AMSL) are found on the north-facing slopes of the Qilian Mountains (Fig. 1). Finally, isolated patches of conifer forests consisting of mostly Qinghai spruce (*Picea crassifolia*; Carpenter, 2001b) are found throughout the Qilian Mountains. The natural landscape of the study area comprises of mountains, oases, and deserts, all interrelating with each other (Ma & Veroustraete,