Atmospheric Research 137 (2014) 145–166

Contents lists available at ScienceDirect

Atmospheric Research

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

Uncertainty analysis of bias from satellite rainfall estimates using copula method

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ARTICLE INFO

Article history:
Received 20 December 2012
Received in revised form 16 August 2013
Accepted 20 August 2013

Keywords:
Satellite rainfall estimates
PERSIANN
TMPA-3B42
Bias-adjustment
Copula
Uncertainty

ABSTRACT

The aim of this study is to develop a copula-based ensemble simulation method for analyzing the uncertainty and adjusting the bias of two high resolution satellite precipitation products (PERSIANN and TMPA-3B42). First, a set of sixty daily rainfall events that each of them occurs concurrently over twenty 0.25° × 0.25° pixels (corresponding to both PERSIANN and TMPA spatial resolution) is determined to perform the simulations and validations. Next, for a number of fifty-four out of sixty (90%) selected events, the differences between rain gauge measurements as reference surface rainfall data and satellite rainfall estimates (SREs) are considered and termed as observed biases. Then, a multivariate Gaussian copula constructed from the multivariate normal distribution is fitted to the observed biases. Afterward, the copula is employed to generate multiple bias fields randomly based on the observed biases. In fact, copula is invariant to monotonic transformations of random variables and thus the generated bias fields have the same spatial dependence structure as that of the observed biases. Finally, the simulated biases are imposed over the original satellite rainfall estimates in order to obtain an ensemble of bias-adjusted rainfall realizations of satellite estimates. The study area selected for the implementation of the proposed methodology is a region in the southwestern part of Iran. The reliability and performance of the developed model in regard to bias correction of SREs are examined for a number of six out of those sixty (10%) daily rainfall events. Note that these six selected events have not participated in the steps of bias generation. In addition, three statistical indices including bias, root mean square error (RMSE), and correlation coefficient (CC) are used to evaluate the model. The results indicate that RMSE is improved by 35.42% and 36.66%, CC by 17.24% and 14.89%, and bias by 88.41% and 64.10% for bias-adjusted PERSIANN and TMPA-3B42 estimates, respectively.

1. Introduction

High resolution satellite rainfall estimates (SREs) provide a useful source of data (i.e. uninterrupted and global coverage) for hydrological applications and water resources planning, particularly over developing regions in which ground-based observations are usually sparse or unevenly distributed. However, using satellite products is subject to error and uncertainty due to the indirect nature of their estimates. On the other hand, reliable estimation of precipitation is essential for hydrologists, as the uncertainties associated with rainfall estimates will propagate in hydrologic modeling predictions (Aghakouchak, 2010). Therefore, in this study, the authors focus on the bias simulation and adjustment of two widely used high resolution satellite products (PERSIANN and TMPA-3B42) over a region in the southwest of Iran.

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0169-8095/$ – see front matter
http://dx.doi.org/10.1016/j.atmosres.2013.08.016

The evaluation of the accuracy of SREs has been carried out at different spatial and temporal resolutions in several studies in the last years (Tian et al., 2007; Hong et al., 2007; Su et al., 2008; Li et al., 2009; AghaKouchak et al., 2009, 2012; Hirpa et al., 2010; Dinku et al., 2010; Behrangi et al., 2011; Bitew and Gebremichael, 2011; Yong et al., 2012). However, the applicability of SREs in hydrologic predictions and water resources management is limited, due to a lack of quantitative information regarding the uncertainties of satellite precipitation estimates at required spatial and temporal resolution (Sorooshian et al., 2000).

One way to assess spatio-temporal uncertainties of satellite precipitation products is to simulate an ensemble of precipitation fields which consists of a large number of realizations; each realization represents a possible rainfall event (Aghakouchak, 2010). Hossain and Anagnostou (2006) developed a two-dimensional satellite rainfall error model (SREM2D) for simulating ensembles of satellite rain fields. They characterized the joint spatial probability of successful delineation of rainy and non-rainy areas using Bernoulli trials of the uniform distribution with a correlated structure generated based on Gaussian random fields. They also generated random error fields of SREs by Monte Carlo simulation of given realizations. Bellerby and Sun (2005) proposed a methodology to quantify the uncertainty present in high-resolution satellite precipitation estimates by generating probabilistic and ensemble representations of the measured precipitation field. Teo and Grimes (2007) described an approach for estimating the uncertainty on satellite-based rainfall values using ensemble generation of rainfall fields based on the stochastic calibration. They obtained the correct spatial correlation structure within each ensemble member by the use of geostatistical sequential simulation. Hong et al. (2006a,b) developed an uncertainty analysis framework to quantify PERSIANN-CCS precipitation estimates error characteristics into a range of discrete temporal (1, 3, 6, 12, and 24 h) and spatial (0.04°, 0.12°, 0.24°, 0.48°, and 0.96°) scales. They also generated ensemble members of precipitation data as forcing input to a conceptual rainfall-runoff hydrologic model using Monte Carlo simulation to examine the influence of precipitation estimation error on the uncertainty of hydrological response.

Note that in the aforementioned studies, the geostatistical approaches and Monte Carlo simulation were used to generate spatially correlated random fields and ensemble members of precipitation estimation error. Compared with a single best estimate, such ensemble-based models can provide more accurate quantification of precipitation uncertainty; however, geostatistical based methods (e.g. a simple variogram model or a covariance matrix) have some limitations. For example in data analysis by geostatistical models, the data should have three features including dependency, stationarity, and Gaussian distribution (Johnston, 2004). Also, in models like geostatistical sequential simulation which uses classical families of multivariate distributions such as bivariate normal, log-normal and gamma, dependence structure between variables is not independent on the choice of the marginal distributions (Genest and Favre, 2007). Therefore, using such models may lead to unrealistic simulations (Germann et al., 2006). Therefore, as an alternative approach, copulas that are joint cumulative distribution functions can be employed to describe the dependence structure of variables as well as to model multivariate random variables with different marginal distributions. In fact, describing the dependence structure independent of the marginal distribution is one of the most attractive features of copulas (Joe, 1997; Nelsen, 2006; Aghakouchak, 2010).

In recent years, several studies in regard to applications of different families of copula in hydrological and meteorological processes have been reported by Grimaldi and Serinaldi (2006), Renard and Lang (2007), Zhang and Singh (2007), Evin and Favre (2008), Serinaldi (2009a,b), Wang et al. (2010), Aghakouchak et al. (2010a,b,c), and Vandenberghe et al. (2010). In this study, we assess the uncertainty and adjust the bias of PERSIANN and TMPA-3B42 products using a copula-based ensemble generation method. For this reason, a multivariate Gaussian copula is employed to describe the dependence structure and to simulate multivariate satellite rainfall bias fields based on the observed biases of daily rainfall events over twenty $0.25^\circ \times 0.25^\circ$ pixels. It is pointed out that the daily resolution of SREs is used in this paper because the reference rain gauge data are based on the daily measurements. Indeed, there doesn't exist a reliable set of sub-daily ground data across the study area.

The approach presented here is similar to that of Aghakouchak et al. (2010a,b,c) since it makes use of copula technique to generate an ensemble of rainfall realizations. However, in the proposed model by Aghakouchak et al. (2010a, b,c), the intention was to use copula-based simulation of multivariate error fields for radar rainfall estimates in order to generate an ensemble of rainfall realizations, while the aim of this study is to develop a bias correction model for satellite precipitation estimates. For this purpose, multiple bias fields are generated based on the observed biases of fifty-four daily rainfall events over twenty $0.25^\circ \times 0.25^\circ$ pixels. Then, the generated biases are imposed over the original SREs in order to simulate an ensemble of bias-adjusted rainfall realizations of satellite estimates. To examine the reliability and performance of the developed model, the generated biases are also imposed over the six daily rainfall events which have not been involved in the steps of bias simulation. It is noted that these six selected events have occurred over the same pixels as those fifty-four events. In addition, the model presented here uses an uncertainty analysis technique (see Section 3.5) to select a more accurate set of biases among the several randomly generated sets which would result in better estimates.

It is worth pointing out that the 3B42 version of TMPA products presents the bias reduction data of precipitation estimates using the gauge data based on the Global Precipitation Climatology Project (GPCP) monthly rain gauge analysis (Rudolf, 1993). The gauge adjustment process involves aggregating both the gauge and the 3-hourly 3B42 estimates to a monthly scale and then applying the ratio of the 3B42/gauge monthly totals to each 3-hourly time step (Habib et al., 2009). However, several studies have reported the uncertainty associated with the TMPA-3B42 product over different regions (Jiang et al., 2012; AghaKouchak et al., 2009, 2011; Habib et al., 2009; Yong et al., 2012). Compared with TMPA-3B42 algorithm that assumes the precipitation estimation error as a fixed ratio of rain rates, the framework proposed based on the simulated ensembles of SREs bias fields provides more realistic quantification of uncertainties associated with different kinds of satellite precipitation products (Hong et al., 2006a,b).