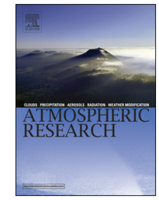
Atmospheric Research 164–165 (2015) 37–48

Contents lists available at ScienceDirect

Atmospheric Research

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



Hydrologic evaluation of satellite and reanalysis precipitation datasets over a mid-latitude basin

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ARTICLE INFO

Article history:
Received 28 December 2014
Received in revised form 24 March 2015
Accepted 29 March 2015
Available online 25 April 2015

Keywords:
Hydrologic modeling
Precipitation
Remote sensing

ABSTRACT

Using precipitation data from satellite or global reanalysis products to force hydrologic models exhibits complex rainfall error and resolution effects in the simulation of streamflows. This study assesses the error propagation of two global (or near-global) precipitation datasets in terms of flood modeling for a range of basin scales (300–70,000 km^2) focusing on multi-year (2002–2011) simulations over a mid-latitude basin (Susquehanna River Basin) in the Northeastern United States. These datasets are the TRMM Multi-satellite Precipitation Analysis 3B42V7 (TRMM3B42V7) research product and the Global Land Data Assimilation (GLDAS) reanalysis system precipitation dataset, which represent 3-hourly rainfall time series at 25-km and hourly time series at 100-km spatial grid resolutions, respectively. The precipitation products, aggregated to a common 3-hourly time resolution, are used to force a distributed hydrologic model (Hillslope River Routing – HRR) for moderate and heavy precipitation events over the basin. The NCEP multi-sensor precipitation analysis (Stage IV) is used as the reference rainfall field for the evaluation of the precipitation and hydrologic simulation errors. Results show that the satellite product exhibits significantly better error statistics compared to the GLDAS. Particularly for the simulated streamflow, GLDAS is shown to have up to 7 (3) times higher mean relative error compared to the corresponding TRMM3B42V7 error metric for moderate (extreme) streamflow values. This significant divergence in the runoff simulation error statistics is attributed to differences between the two precipitation products in terms of the propagation of their error properties from precipitation to simulated streamflow. Significant improvement of the statistical scores (up to 50%) with increasing basin size is shown for the satellite product; this basin scale effect is marginal for the GLDAS product.

1. Introduction

Developing global hydrologic modeling systems that can support flood warning and flood risk analysis studies has been an aim of research efforts in hydrology (Hong et al., 2007; Shrestha et al., 2008; Wu et al., 2012). Modeling a basin's flood response requires an accurate spatio-temporal characterization of precipitation variability within the basin. Estimates of precipitation at sub-basin scales are typically based on weather radar observations and/or gauge network measurements (Ogden et al., 2000; Vivoni et al., 2006). However, recent advances in multi-satellite rainfall retrievals have allowed uses of high-resolution satellite rainfall products in flood modeling applications (Bitew and Gebremichael, 2011a; Yong et al., 2012). The high-resolution satellite products are particularly important by the fact that traditional ground-based observations have significant spatial coverage gaps over remote and ungauged regions of earth (Asadullah et al., 2008; Dai et al., 2007; Hossain and Huffman, 2008; Sapiano and Arkin, 2009). Some of the high resolution, near-global scale, multi-satellite-sensor rainfall products include TRMM3B42V7, TRMM3B42RT (Huffman et al., 2007), CPC MORPHing technique-CMORPH (Joyce et al., 2004), Precipitation Estimation from Remote Sensing Information using Artificial Neural Network-PERSIANN (Sorooshian et al., 2000), Hydro-estimator (Scofield and Kuligowski, 2003), Naval Research Laboratory Blending algorithm-NRLBLD (Turk and Miller, 2005), and Global Satellite Mapping of Precipitation-GSMaP (Ushio and Kachi, 2009). These products use different combinations of information from geostationary infrared (IR) and low earth orbit satellite microwave (MW) observations. The satellite rainfall product used in this study is the TRMM3B42V7 that is available at a 3 hourly temporal resolution and 25-km spatial resolution. The TRMM3B42 algorithm suite uses more accurate, but infrequent, MW rainfall estimates to calibrate a rainfall algorithm applied on the less direct, but frequent, IR observations. The merging technique then uses the IR-based rainfall estimates to fill in gaps where MW data

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http://dx.doi.org/10.1016/j.atmosres.2015.03.019

are not available. The TRMM3B42RT product is available in near real-time, while the TRMM3B42V7 is a gauge-adjusted product available with two to three month latency.

A typical reanalysis system consists of two main components, the forecast system and the data assimilation system. The role of the data assimilation system is merging available observational data with the forecast model simulations. Global retrospective analyses (reanalysis) products can provide long-term hydrologic datasets that can support global frequency analyses of hydrologic extremes (e.g. floods, droughts). Widely used reanalysis products include a 44-year reanalysis from the Global Data Assimilation System (GDAS) from the National Center for Environmental Prediction (NCEP) (Kalnay et al., 1996), a 40-yr reanalysis (ERA-40) from the European Centre for Medium-Range Weather Forecasts (ECMWF) (Bosilovich et al., 2008; Uppala et al., 2005), ERA-Interim (Dee et al., 2011), and a 35-year reanalysis from the Global Land Data Assimilation System (GLDAS) of NASA's Goddard Space Flight Center (GSFC) (Rodell et al., 2004). The GLDAS precipitation data used in this study consist of outputs from a regional climate model plus spatially and temporally integrated datasets from radar, rain gauges and satellite observations. They are available at hourly temporal scale and approximately 100 km spatial grid resolution.

Numerous satellite rainfall validation studies have been carried out to provide a better and deeper understanding about the uncertainties associated with the remotely sensed precipitation products over different regions (Adler et al., 2001; AghaKouchak et al., 2009; Alemohammad et al., 2014; Brown, 2006; Dinku et al., 2007; Ebert et al., 2007; Gottschalck et al., 2005; Krajewski et al., 2000; McCollum et al., 2002; Stampoulis et al., 2013; Su et al., 2008; Tang et al., 2010). Studies have shown that the accuracy of satellite rainfall products depends on the rainfall type (e.g. convective vs. stratiform), topography, and climatological factors; for instance CMORPH has been shown to underestimate precipitation during hurricane Wilma (Turk et al., 2006), and overestimate precipitation over both South (Demaria et al., 2011) and North America (AghaKouchak et al., 2011).

In addition to the rainfall error analysis, studies have investigated accuracies of hydrological modeling forced with satellite rainfall data. Behrangi et al. (2011) investigated the feasibility of simulating streamflows for mid-size basins by forcing a hydrologic model with different satellite-based precipitation products (TRMM3B42V7 and RT, CMORPH, PERSIANN). They concluded that bias-adjustment of satellite products has a significant impact on capturing streamflow patterns and magnitude. Beighley et al. (2011) predicted streamflows by forcing the HRR hydrologic model with three satellite derived precipitation datasets (TRMM3B42V6, CMORPH, PERSIANN) over the Congo Basin. They argued that all three satellite products are unreasonably overestimating over equatorial regions. However, the TRMM3B42V6 product exhibited the best performance in terms of rainfall data quality and simulated streamflows. Su et al. (2008) evaluated the skill of streamflow simulations from a semi-distributed hydrology model driven with TRMM3B42V6 rainfall data versus simulations driven with rain gauge rainfall measurements. The research demonstrated a good agreement between reference and satellite precipitation data for streamflow simulation at seasonal and inter-annual time scales, although there was an overestimation at the daily time scale. They recommended TRMM3B42V6 for hydrological simulations in ungauged areas. Gourley et al. (2011), on the other hand, evaluated rainfall estimates from TRMM3B42V6 and PERSIANN-CCS in comparison to radar rainfall estimates for hydrological simulations over the Ft. Cobb basin (342 km^2). The study highlighted the importance of considering rainfall products resolution on hydrologic model calibration. They also demonstrated that TRMM3B42V6 has relatively better performance than PERSIANN-CCS. However, the study was carried out over a small watershed as well as short period of time (3 months). Vergara et al. (2014) underlined the effect of rainfall data resolution and basin scale on hydrological simulations using TRMM3B42RT and MPE (Multi-sensor Precipitation Estimator) radar data over 5 medium size sub-basins. The study was limited to only one product and a small to medium range of basin scales (500–5000 km2). Maggioni et al. (2013) investigated the error propagation from TRMM3B42 (V7 and RT), CMORPH, and PERSIANN-CCS precipitation estimates on runoff simulations. The study was over a 2 year period and focused on small to medium size basin scales (500–5000 km^2). The results demonstrated significant dependency of error propagation to catchment area. Nikolopoulos et al. (2012) evaluated TRMM3B42V6, CMORPH, and PERSIANN-CSS precipitation estimates for a major flash flood event simulation through forcing a distributed hydrologic model. They demonstrated that the examined products do not perform satisfactorily on capturing the flood peak from this complex terrain heavy precipitation event. Bitew and Gebremichael (2011b) in an earlier study also evaluated various global satellite precipitation products for stream flow simulations over two small basins in Ethiopia through forcing a semi-distributed hydrologic model. They demonstrated that TRMM3B42RT and CMORPH are performing better than TRMM3B42V6 and PERSIANN. They claimed that the gauge adjustment in TRMM3B42V6 made the data set worse than the real-time (unadjusted) product. In general the product resolution, catchment size and hydrologic model calibration are influential parameters on quality of generated runoff through gridded precipitation products. Most of the above studies have been limited to small or mid-size basins and short simulation periods, while only few of them have considered heavy precipitation events. More in-depth analysis of the precipitation error propagation in streamflow simulations is needed to demonstrate utility of satellite precipitation product in flood modeling. The studies must account for comprehensive ranges of basin scales and event severities.

In this study, the TRMM3B42V7 satellite rainfall product and the GLDAS reanalysis precipitation datasets are evaluated against multi-year (2002–2011) high-quality and resolution radar-rainfall data over multi-scale (300–70,000 km^2) mid-latitudes basins in the Northeast United States to assess their applicability in basin flow simulations. Streamflow simulations are based on the HRR model, which has been used in past regional hydrologic modeling applications of satellite rainfall (Beighley et al., 2009; Beighley et al., 2011). The study provides a new insight on the combined effect of precipitation product (spatial resolution and accuracy) and basin scale in the error propagation from precipitation to flood prediction contrasting higher-resolution satellite precipitation estimates to a reanalysis precipitation product. The focus of the error analysis is on moderate to heavy precipitation events, which are defined as events falling between the 75th and 90th and greater than 90th percentiles of events that occurred over the study area during 2002–2011, respectively. Comparison between the satellite (TRMM3B42V7) and GLDAS reanalysis precipitation datasets provide an insight of the expected benefits from using current near-global-scale satellite products, relative to the longer-term, but coarser spatial resolution, global reanalysis precipitation datasets, in terms of hydrologic simulations. The temporal resolution dependency is neglected since all precipitation datasets were aggregated to the 3-hourly time scale.

In the next section we present the study area and data, while Section 3 presents the implemented data processing and matching techniques. Section 4 describes the hydrologic modeling framework. Finally, Section 5 presents the error analysis and hydrologic error propagation results. Conclusions and recommendations are presented in Section 6.

2. Study area and data

The study area is the Susquehanna River Basin in the Northeast United States with a domain ranging from 39 N to 43 N and 75 W to 79 W (Fig. 1). The region has an elevation gradient from north to south-east, with the highest peak in northwestern corner and the lowest point in the southeastern corner. The total area of Susquehanna River Basin is 71,000 km^2, of which 76% is in Pennsylvania, 23% in New York, and 1% in Maryland. Cumulating the drainage areas along