Atmospheric Research 132–133 (2013) 223–238

Contents lists available at ScienceDirect

Atmospheric Research

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

Performance evaluation of merged satellite rainfall products based on spatial and seasonal signatures of hydrologic predictability

Abebe Gebregiorgis, Faisal Hossain *

Department of Civil and Environmental Engineering, Tennessee Technological University, Cookeville, TN 38505-0001, USA

ARTICLE INFO

Article history:
Received 12 January 2013
Received in revised form 20 April 2013
Accepted 9 May 2013

Keywords:
Satellite rainfall
Uncertainty
Stream flow
Runoff predictability
Merging

ABSTRACT

Despite the inherent estimation uncertainty, remote sensing based rainfall data have enormous value for stream flow simulation. Recent investigations have shown that the historical performance of satellite products in hydrologic prediction can be a useful (diagnostic) proxy for merging products to a more superior performing state for prognostic simulations (i.e., forward in time). Using a hydrologic model set-up over the entire Mississippi River Basin (MRB) and three widely used satellite rainfall products (3B42RT, CMORPH and PERSIANN-CCS), this study explored a merging scheme based on runoff predictability. The spatial and temporal signatures of variability were closely investigated to understand the impact on prediction skill of the merging scheme. The spatial variability (i.e., non-uniform) considered the grid box by grid box variation at the native resolution of individual satellite products, while the temporal variability (i.e., non-stationary) was confined to variation in 3 month-long seasons (winter, spring, summer and fall). When both the spatial and temporal variability in runoff predictability was leveraged, the merging scheme yielded the largest improvement over individual product's performance forward in time. During an independent validation assessment, the stream flow simulated by the merged product was more strongly correlated with observed discharge (than individual products) at 12 gauging stations. In terms of reduction in root mean squared error (RMSE), the merged product showed an improvement of 57% for 3B42RT, 63% for CMORPH and 68% for PERSIANN-CCS products. The investigation clearly showed that any 'operational' and hydrologic predictability-based merging scheme for unifying available satellite rainfall products must factor in both the spatial and temporal signatures of runoff predictability to achieve consistently more superior prognostic skill.

1. Introduction

Precipitation (hereafter 'precipitation' is used interchangeably with 'rainfall') is a major atmospheric flux that appears in the form of fog, snow, and rain. It is the central component of the hydrologic cycle that controls the overall land surface hydrological system and it is, therefore, the most important input to hydrological models (Coe, 2000; Nijssen and Lettenmaier, 2004). Generally speaking, the estimation accuracy of precipitation dictates the predictive ability of hydrologic models to capture the basin responses at all space–time scales (Hong et al., 2006). On the other hand, evaporation from open water and bare soil surfaces and evapotranspiration from vegetated surfaces hold the transfer of fluxes from the land surface to the atmosphere. They too, play an important role in hydrologic cycle in determining surface temperature, pressure, and rainfall.

A key and useful terrestrial component of the hydrologic cycle is runoff, which is the part of the precipitation that remains after evapo-transpiration, infiltration and other possible abstractions. There are two major factors that influence the formation of runoff: climatic and physiographic factors (Shelton, 2009). Precipitation is a climatic factor that

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* Corresponding author at: Department of Civil and Environmental Engineering, Tennessee Technological University, 1020 Stadium Drive, Boc 5015, Cookeville, TN 38505, USA. Tel.: +1 9313723257.

0169-8095/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.atmosres.2013.05.003

provides moisture supply for the formation of runoff after fulfilling infiltration, evaporation and canopy interception. Therefore, understanding of the spatial and temporal nature of rainfall (distribution and intensity) is an important factor to understanding the dynamic nature of runoff processes. The other climatic factor, evapotranspiration, also determines the amount of moisture allocated for runoff. The physiographic factors, such as soil type, ground water condition and land use and cover, influence the availability of soil moisture that eventually determines the runoff generation.

In general, precipitation, evapotranspiration, soil moisture, and excess runoff are the most important hydro-climatic processes that functionally integrate as stream flow. These physical processes collectively transform the precipitation into the more measurable basin response as stream flow. Nowadays, in response to the paucity of in-situ/ground measurements, model-based prediction of soil moisture, evapotranspiration, and runoff is often used as the primary source for information on soil wetness for large scale studies. This is based on the argument that precipitation is the most dominant player in land surface hydrology and will therefore dictate land surface flux variability. However, ground based precipitation is difficult to obtain at regional and global scales on a regular basis and at high spatial and temporal resolutions.

As a concept, the ability to determine the spatial and temporal distributions of land surface fluxes based on satellite rainfall data is therefore a significant step forward in understanding the Earth as an integrated system (Hoeben and Troch, 2000; Bindlish and Barros, 2001; Haider et al., 2004; Peters-Lidard et al., 2008; Hong et al., 2007; Gebremichael et al., 2010). In this regard, the planned Global Precipitation Measurement (GPM) mission will usher in a new era on precipitation measurement from space in terms of higher spatial resolution, global extent and frequency of sampling of rainfall (Hou et al., 2008). GPM holds great promise for prediction of surface hydrologic phenomenon in research and operational sectors. With GPM, precipitation measurement from space will be available at spatial resolutions of 25–100 km^2 and temporal scales of 3 to 6 h for about 90% of global coverage (Hou et al., 2008).

While the current operational satellite rainfall algorithms provide global precipitation estimates at relevant spatial and temporal scales for hydrologic simulation, many studies have reported high uncertainty associated with satellite precipitation products (Hossain and Anagnostou, 2004; Hong et al., 2006; Hossain and Huffman, 2008; Peters-Lidard et al., 2008; Zeweldi and Gebremichael, 2009; Bitew and Gebremichael, 2010; Gebregiorgis and Hossain, 2011, 2012; Gebregiorgis et al., in press). Different satellite rainfall products have their own unique algorithm to drive the rainfall estimation process. For example, the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) product is a merged satellite rainfall estimate from Passive Microwave (PMW) sensors at low earth orbits and Infrared (IR) sensors at geostationary orbits (Huffman et al., 2007). The TMPA merged product (e.g. 3B42RT) takes advantage of the strength from both sensors (accurate surface precipitation estimate from PMW and better sampling from IR). Climate Prediction Center (CPC) morphing (generally called "CMORPH") is another type of precipitation estimate algorithm from PMW and IR sensors. This algorithm produces propagation vector matrices from geostationary IR data and applies to propagate the PMW estimates in time and space when the real PMW data is unavailable (Joyce et al., 2004). Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Cloud Classification System (PERSIANN-CCS) uses neural network function to merge high quality and sparsely sampled rainfall data with better temporally sampled data from low orbital and geostationary satellites, respectively (Hsu et al., 2010; Sorooshian et al., 2000).

The aforementioned algorithms have also been developed directly or indirectly by merging of IR and PMW data based on different approaches to estimate the rainfall magnitude in more accurate way. Thus, these products, even though they utilize similar input datasets, are created using structurally very different approaches. Gebregiorgis and Hossain (2011) conducted merging of three satellite rainfall products (3B42-RT (TMPA), CMORPH and PERSIANN-CCS) based on hydrologic predictability (error variance of soil moisture and runoff) to exploit any potential complementary advantage of the three different approaches. The spatial and temporal hydrologic predictability (in runoff and soil moisture) was utilized to derive the a priori relative weight factors for each product and each grid box. According to that study (Gebregiorgis and Hossain, 2011), the runoff based merged rainfall product captured the high flow regime, while the soil moisture based merged product simulated the low flow regime considerably better when compared to the performance of individual satellite products on an independent assessment period.

The merging scheme of Gebregiorgis and Hossain (2011) is based only on the spatial signature of variability (i.e., non-uniform) in the merging weights across the grid boxes. The relative weights for each grid box are assumed stationary. Herein, the term 'stationary' is analogous to the word 'steady' that is often used to characterize flow regimes, and should therefore not be construed as a systematic change in statistics. Because hydro-climatic processes display significant spatial and temporal variations at the watershed level, it is worthwhile to explore both the spatial and temporal heterogeneities as 'signatures' (i.e., the unsteady and non-uniform pattern) when implementing the merging technique for satellite rainfall products. The spatial variability of soil moisture and runoff errors occurs due to the variation of magnitude of meteorological parameters (rainfall, temperature, wind speed, air pressure, etc.) within the region; due to noticeable diversity of soil characteristics and land use land cover from place to place; due to non-uniform nature of topography within the basin. In addition to the spatial variation, some of the above governing factors, such as the meteorological parameters and land use land cover, also display significant heterogeneity from season to season, altering the temporal nature of soil moisture and runoff errors.

Therefore, to understand the impact of spatial and temporal variations on performance skill, any merging scheme, based on relative weighting of products to a more superior state, needs to be tested in the continuum of space and time. There are four scenarios that need a careful investigation, notably: 1) spatially and temporally varying weight factors (i.e., non-uniform and non-stationary), 2) spatially varying and temporally uniform weight factors (i.e., non-uniform and stationary); 3) spatially and temporally uniform weight factors (i.e., uniform and stationary); and 4) simple average of three high resolution satellite rainfall products (3B42RT, CMORPH and PERSIANN-CCS).