Advances in Water Resources 83 (2015) 190–206

Contents lists available at ScienceDirect

Advances in Water Resources

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

Hyperresolution hydrologic modeling in a regional watershed and its interpretation using empirical orthogonal functions

Giuseppe Mascaro[a,b,*], Enrique R. Vivoni[a,c], Luis A. Méndez-Barroso[c,d]

[a] School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ, USA
[b] Julie Ann Wrigley Global Institute of Sustainability, Arizona State University, Tempe, AZ, USA
[c] School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA
[d] Departamento de Ciencias del Agua y Medio Ambiente, Instituto Tecnólogico de Sonora, Ciudad Obregón, Sonora, Mexico

ARTICLE INFO

Article history:
Received 25 February 2015
Revised 22 May 2015
Accepted 27 May 2015
Available online 10 June 2015

Keywords:
Distributed hydrologic model
Catchment hydrology
North American monsoon
Principal component analysis
High performance computing

ABSTRACT

Hyperresolution (<1 km) hydrologic modeling of regional watersheds is expected to support a broad range of terrestrial water cycle studies, but its feasibility is still challenging due to process, data and computational constraints, as well as difficulties in interpreting the high-dimensional dataset of spatiotemporal model forcings and outputs. We address some of these modeling challenges by extending the application of a physically-based, distributed hydrologic model to the Río San Miguel watershed (3796 km^2) in Mexico based on prior efforts that demonstrated the process fidelity at smaller spatiotemporal scales. Long-term (7 year) simulations are conducted at a hyperresolution (∼78 m) over the large domain using parallel simulation capabilities. To address data sparseness, we develop strategies to integrate ground, remotely-sensed and reanalysis data for setting up, forcing and parameterizing the model. Complementary tests with observations at individual stations and remotely-sensed spatial patterns reveal a robust model performance. After building confidence in the model, we interpret the spatiotemporal model forcings and outputs using empirical orthogonal functions (EOFs) analyses. For all model outputs, a large portion (58–80%) of the spatiotemporal variability can be explained by two dominant EOFs, which are related to model forcings and basin properties. Terrain controls on soil water accumulation have a marked impact on the spatial distribution of most hydrologic variables during the wet season. In addition, soil properties affect soil moisture patterns, while vegetation and elevation distributions influence evapotranspiration and runoff fields. Given the large outputs from long-term hyperresolution simulations, EOF analyses provide a promising avenue for extracting meaningful hydrologic information within complex, regional watersheds.

1. Introduction

Distributed hydrologic models (DHMs) are useful for simulating the terrestrial water cycle and its spatiotemporal variability in large domains. For example, DHMs provide support for assessments of water availability, sustainability and security [12,67], management of agriculture and land use to assure food security [28,69,75] and prediction of hydrologic extremes, including floods and droughts [21,41,58,87]. Taking advantage of the continuously increasing resolution, frequency and availability of remotely-sensed observations, the applications of DHMs are expected to grow in the context of climate change impacts and increasing water demands [1,86]. DHMs are also used to provide initial conditions to weather prediction models [e.g. [70]], to quantify the effects of climate model forcings at the land surface [e.g. [73]] and to set hydrologic feedbacks for models of vegetation dynamics [e.g. [33,46]]. Furthermore, DHMs allow advancing the basic knowledge of hydrologic processes, including the identification of dominant spatiotemporal patterns and their physical controls across different climatic regimes [42,71,84].

Recently, Wood et al. [88] called the hydrologic community to increase the spatial resolution of DHMs up to hyperresolutions of ∼1 km at global scales and ∼100 m at regional and continental scales (10^3–10^6 km^2). By capturing the spatial variability of land surface properties with a greater detail, hyperresolution simulations have the potential to improve the representation of hydrologic dynamics in the terrestrial water cycle. To be effective, however, hyperresolution simulations require process models with a relatively high fidelity, but computational constraints and limited data availability, resolution and coverage have usually prevented their application in large domains. For example, DHMs are typically used at a spatial resolution of 50–100 km at global scales [e.g. [67]] and at 1–10 km resolution

* Corresponding author at: School of Sustainable Engineering and the Built Environment, Arizona State University, ISTB4, Building 75, Room 778b, Tempe, AZ 85287-6004, United States. Tel.: +1 (480) 7273573; fax: +1 390706755310.
E-mail address: gmascaro@asu.edu (G. Mascaro).

http://dx.doi.org/10.1016/j.advwatres.2015.05.023
0309-1708/

in regional and continental watersheds [e.g. [6,44,71]]. As a result of this coarse resolution, physical processes are often highly conceptualized and lateral water transfer in the subsurface may be neglected. For higher resolution applications, a different class of DHMs is able to represent hydrologic processes with a higher fidelity, including surface and subsurface flows in two or three dimensions and the coupled feedbacks between water and energy fluxes [e.g. [7,16,31,50,60]]. While these models have ideal characteristics for hyperresolution simulations, their computational burden has typically limited their application to small and medium (less than 10^3 km^2) catchments [e.g. [2,8,9,38,48,72,89]].

Thus, the feasibility of hyperresolution modeling of large watersheds requires addressing several challenges due to tradeoffs between hydrologic process complexity and fidelity, the availability and quality of data needed for model forcing and testing, and the computational resources to conduct the simulations within reasonable time frames. A first challenge is improving the model physics used for terrestrial water cycle dynamics, including enhancing the capability to simulate surface–subsurface interactions and land–atmosphere feedbacks, among other components [88]. A second difficult task is calibrating, testing and creating the forcings for hyperresolution DHMs applied over regional watersheds where limited ground observations might be available. Strategies are required to (i) transfer information derived from limited observations at individual sites over larger areas, (ii) evaluate the model ability to capture spatial patterns of the hydrologic response [25] and (iii) create distributed forcings by integrating available ground data with other sources such as reanalysis products [e.g. [27,54]]. A third challenge for hyperresolution modeling is meeting the computational demands of representing vast amounts of model data through the use of high performance computing clusters [e.g. [39,45,83]].

In addition to difficulties related to computational, model structure, and data limitations, another crucial challenge is the manipulation, interpretation and visualization of the high-dimensional, non-linear datasets generated by hyperresolution simulations. As a result, there is a need to design or adapt tools that facilitate these tasks. In climate and atmospheric sciences, the empirical orthogonal function (EOF) analysis is a powerful method extensively used to analyze large spatiotemporal model outputs [26]. This technique is then extremely suitable to interpret large hydrologic datasets, as it allows (i) capturing the dominant patterns that explain most of the spatial variability, (ii) comparing these patterns with other high-resolution spatial fields including basin properties and atmospheric forcings, and (iii) tracking how the weight of these patterns evolve in time. While previous studies have used EOF analysis to explore rainfall [17], soil moisture [34,37] and streamflow data [23], as well as outputs of coarse resolution models [43,68,74], this technique has not been applied to hyperresolution hydrologic simulations.

In this study, we explore the feasibility of long-term hyperresolution simulations in a regional watershed, the Río San Miguel (RSM) in northwest Mexico, using a physically-based DHM known as the TIN-based Real-Time Integrated Basin Simulator (tRIBS) [31,32]. We conduct simulations at a nominal resolution of ~78 m over a period of 7 years. The RSM basin represents a challenging study site for hyperresolution simulations due to its complex hydrologic response resulting from the interaction of heterogeneous terrain and soil properties with a seasonal, semiarid climate dominated by the North American monsoon that dramatically affects ecosystem properties. Previously, tRIBS has been applied in this region to small catchments (<100 km^2) during summer periods [53,61,81,89], demonstrating the potential of these hyperresolution simulations to capture the spatiotemporal variability of the hydrologic processes. Building upon these previous works, we extend the spatial scale of the simulations up to a regional watershed and their duration from the summer months to a multi-year period.

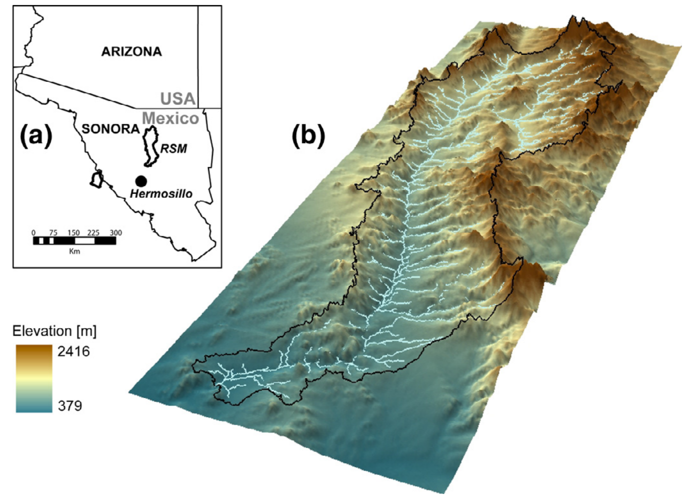

Fig. 1. (a) Location of the RSM basin in Sonora, Mexico. (b) Three-dimensional representation of the watershed boundary, terrain characteristics and channel network of the RSM.

We pursue two main objectives that address some of the main challenges of hyperresolution simulations of large, complex hydrologic systems. First, we design strategies to setup, test and apply a hyperresolution DHM in a region with sparse hydrologic data. For this aim, we (i) integrated datasets from different sources including ground stations, remote sensing and reanalysis products, (ii) designed procedures to create model forcings and parameterize the model with high-resolution products and (iii) developed methods to gain confidence in simulating the spatiotemporal hydrologic response. To meet the computational demands, the hyperresolution simulations were conducted on a high performance computing cluster. Second, we interpret the spatiotemporal variability of the large datasets of model forcings and outputs using the EOF analysis. For this aim, we captured the dominant patterns that explain the spatial variability of the main hydrologic variables and compared them with basin properties and meteorological and vegetation forcings. We tracked how the weight of these patterns and their correlation evolved in time during annual and seasonal periods with the aim of exploring the feedbacks among the variables of the hydrologic system and identifying the physical controls. The strategies presented here to pursue our two main goals are intended to be applicable to a broad range of DHMs applied in diverse settings.

2. Study area and datasets

2.1. Basin characteristics

The study area is the RSM basin (3796 km^2), one of the three main tributaries of the Sonora River [61] located in Sonora, Mexico (Fig. 1a). The climate of the region is arid to semiarid with hot conditions and winter temperatures mostly above 0 °C. The mean annual precipitation ranges from 350 mm to 750 mm depending on location [49,80]. The precipitation regime in northwest Mexico is complex as it is characterized by: (i) a strong seasonality, with relatively wet summers from July to September when 40–80% of the annual precipitation occurs during the North American monsoon [e.g. [23,56]], (ii) a high spatiotemporal variability due to distinct weather systems and to the effect of complex terrain [22,35,49,62] and (iii) high inter-annual and inter-decadal variability associated with teleconnections [20,23].

Topography in the RSM basin is rugged with a mean elevation of 1000 m and a significant relief of about 2000 m (Fig. 1b) resulting from channel incision [10,78]. The mean slope obtained from a 29-m digital elevation model (DEM) derived from the Advanced