Ecological Modelling 303 (2015) 87–96

Contents lists available at ScienceDirect

Ecological Modelling

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

How well do terrestrial biosphere models simulate coarse-scale runoff in the contiguous United States?

C.R. Schwalm[a,b,*], D.N. Huntzinger[b,c], R.B. Cook[d], Y. Wei[d], I.T. Baker[e], R.P. Neilson[f], B. Poulter[g], Peter Caldwell[h], G. Sun[h], H.Q. Tian[i], N. Zeng[j]

[a] Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, AZ 86011, USA
[b] School of Earth Sciences and Environmental Sustainability, Northern Arizona University, Flagstaff, AZ 86011, USA
[c] Department of Civil Engineering, Construction Management, and Environmental Engineering, Northern Arizona University, Flagstaff, AZ 86011, USA
[d] Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[e] Department of Atmospheric Sciences, Colorado State University, Fort Collins, CO 80523, USA
[f] Pacific Northwest Research Station, USDA Forest Service, Corvallis, OR 97331, USA
[g] Department of Ecology, Montana State University, Bozeman, MT 59717, USA
[h] Southern Research Station, USDA Forest Service, Raleigh, NC 27606, USA
[i] International Center for Climate and Global Change Research School of Forestry and Wildlife Sciences, Auburn University, Auburn, 36849 AL, USA
[j] Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD 20742, USA

A R T I C L E I N F O

Article history:
Received 4 July 2014
Received in revised form 23 January 2015
Accepted 9 February 2015
Available online 11 March 2015

Keywords:
Terrestrial biosphere models
Runoff
Intercomparison
North American Carbon Program
Regional

A B S T R A C T

Significant changes in the water cycle are expected under current global environmental change. Robust assessment of present-day water cycle dynamics at continental to global scales is confounded by shortcomings in the observed record. Modeled assessments also yield conflicting results which are linked to differences in model structure and simulation protocol. Here we compare simulated gridded (1° spatial resolution) runoff from six terrestrial biosphere models (TBMs), seven reanalysis products, and one gridded surface station product in the contiguous United States (CONUS) from 2001 to 2005. We evaluate the consistency of these 14 estimates with stream gauge data, both as depleted flow and corrected for net withdrawals (2005 only), at the CONUS and water resource region scale, as well as examining similarity across TBMs and reanalysis products at the grid cell scale. Mean runoff across all simulated products and regions varies widely (range: 71 to 356 mm yr^{-1}) relative to observed continental-scale runoff (209 or 280 mm yr^{-1} when corrected for net withdrawals). Across all 14 products 8 exhibit Nash–Sutcliffe efficiency values in excess of 0.8 and three are within 10% of the observed value. Region-level mismatch exhibits a weak pattern of overestimation in western and underestimation in eastern regions—although two products are systematically biased across all regions—and largely scales with water use. Although gridded composite TBM and reanalysis runoff show some regional similarities, individual product values are highly variable. At the coarse scales used here we find that progress in better constraining simulated runoff requires standardized forcing data and the explicit incorporation of human effects (e.g., water withdrawals by source, fire, and land use change).

1. Introduction

Water balance calculations are becoming increasingly important for Earth system studies and link directly to the amount of reusable water available for wildland and managed environments, as well as human society. Both a general intensification of the hydrological cycle (Schwalm et al., 2011) and, more specifically, an increase in runoff are expected under climate change (Gerten et al., 2008). While numerous attempts (e.g., Alkama et al., 2011; Dai et al., 2009; Gerten et al., 2008; Haddeland et al., 2011; Milliman et al., 2008; Munier et al., 2012; Syed et al., 2010; Walling and Fang, 2003) have been made to observationally constrain continental to global runoff values large uncertainties remain; linked to *inter alia* spatiotemporal gaps in the observed record and the overall heterogeneity of discharge measurements.

A standard approach to address inconsistent observational records is the use of modeling. However, simulated runoff is similarly variable (e.g., Alkama et al., 2011; Gedney et al., 2006;

* Corresponding author at: Northern Arizona University, Center for Ecosystem Science and Society, Flagstaff, AZ 86011, USA. Tel.: +1 928 523 8413; fax: +1 928 523 7423.
E-mail address: christopher.schwalm@nau.edu (C.R. Schwalm).

http://dx.doi.org/10.1016/j.ecolmodel.2015.02.006
0304-3800/

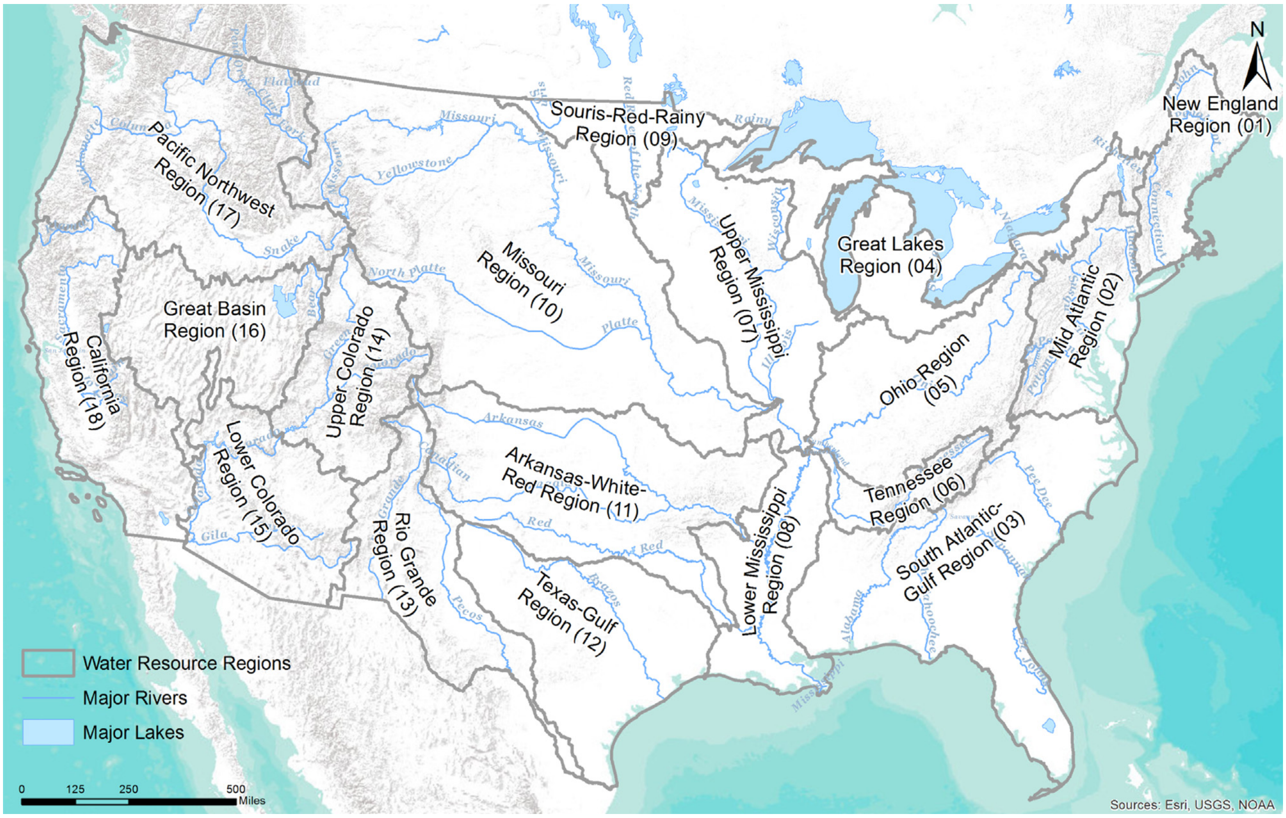

Fig. 1. CONUS water resource regions. USGS water resource regions and major rivers in the CONUS domain. Prior to aggregation of product runoff, regions coverage converted from polygon (http://water.usgs.gov/GIS/huc.html) to 1° raster using the region with the maximum area of overlap for each grid cell.

Haddeland et al., 2011; Shi et al., 2011). Furthermore, large variation in runoff persists even when models use the same meteorological input data (Haddeland et al., 2011). A key source of this ambiguity is the diversity in how models simulate runoff in relation to global environmental change, e.g., changes in precipitation, temperature, net radiation, land cover/use, nitrogen deposition, fire regime, atmospheric concentrations of greenhouse gases, and irrigation (Caldwell et al., 2012; Gerten et al., 2008; Neilson, 1995; Sun et al., 2011). Model forcing data also plays a significant role in simulated runoff magnitude, with the choice of precipitation dataset alone altering simulated region-scale runoff estimates of up to 30% (Biemans et al., 2009). Furthermore, uncertainty in precipitation fields (inter-product spread) may propagate to a similar or greater magnitude of uncertainty in runoff estimates (Fekete et al., 2004).

As a first step to resolve ambiguity in simulated runoff, models must be confronted with observational records. Thus, the objective of this study is to evaluate a suite of modeled runoff estimates in a region with a dense network of stream gauges, the water resource regions (WRRs) of the contiguous United States (CONUS). Specifically, we use TBM simulations from the Regional and Continental Interim-Synthesis (RCIS); a synthesis activity part of the U.S. North American Carbon Program (NACP) with emphasis on the 2000 to 2005 time period (Huntzinger et al., 2012). To provide additional context for RCIS TBM runs we extend our intercomparison with reanalysis- and surface station-based estimates of runoff for the same spatiotemporal domain. Throughout this study we emphasize the coarse scales (from grid cell to CONUS) that typify TBM use as opposed to pristine watersheds and finer scales.

2. Data and methods

We compare observed runoff to 14 modeled runoff estimates. Observed runoff is derived from the *c.* 7400 currently operating stream gauges maintained by the United States Geological Survey (USGS)[1]. This network of stream gauges is organized by hydrologic unit codes (HUC[2]) using a standardized six-level nested hierarchy that, nationally for the United States, varies from 21 water resource regions (WRR) at level one (also called 2-digit HUC or HUC2) to *c.* 160,000 subwatersheds at level six[3]. For this study the 18 WRRs in the CONUS domain (Fig. 1) are used.

Monthly WRR runoff is available directly from the USGS WaterWatch[4] portal. The WRR values are based on daily flow data collected at stream gauges, stream gauge drainage basins, and HUC boundaries. Monthly runoff is computed for each basin by dividing average daily flow (scaled by days per month) by basin drainage area. These stream gauge-specific values are assigned to the target HUC level using area weighting and assuming runoff is uniform across each stream gauge basin. Thus, the WRR values leverage the full network of currently operating stream gauges.

The gridded (1° spatial resolution) monthly TBM runoff values (Table 1) span 2001 to 2005 on a water year basis. A water year is the period from October 1 to September 30 with the water year designation (e.g., 2005) corresponding to the year of the ending date. TBM output is taken from the NACP RCIS (Huntzinger et al., 2012), as well as an additional TBM, WaSSI, that simulates the same spatiotemporal domain as the RCIS but not gridded. The six TBM simulations, an ensemble of opportunity (Allen and Ingram, 2002), are comprised of model output generated from ongoing NACP and related studies. While this precludes attributing model-data mismatch to model structure and/or differences in driver data,

[1] http://waterwatch.usgs.gov/public/flow_stats/dv01d.zip.
[2] http://water.usgs.gov/GIS/huc.html.
[3] ftp://ftp-fc.sc.egov.usda.gov/NCGC/products/watershed/hu-standards.pdf.
[4] http://waterwatch.usgs.gov.