Global and Planetary Change 115 (2014) 1–15

Contents lists available at ScienceDirect

Global and Planetary Change

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

Changes of reference evapotranspiration in the Haihe River Basin: Present observations and future projection from climatic variables through multi-model ensemble

Wanqiu Xing [a,b], Weiguang Wang [a,b,*], Quanxi Shao [c], Shizhang Peng [a], Zhongbo Yu [a,b,d], Bin Yong [a], John Taylor [e]

[a] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China
[b] College of Water Resources and Hydrology, Hohai University, Nanjing 210098, China
[c] CSIRO Mathematics, Informatics and Statistics, Private Bag 5, Wembley, WA 6913, Australia
[d] Department of Geoscience, University of Nevada, Las Vegas, Las Vegas, NV 89154, USA
[e] CSIRO Mathematics, Informatics and Statistics, GPO Box 664, Canberra, ACT 2601, Australia

ARTICLE INFO

Article history:
Received 16 October 2012
Received in revised form 1 December 2013
Accepted 14 January 2014
Available online 23 January 2014

Keywords:
Reference evapotranspiration
Multi-model ensemble
The Haihe River Basin
Bayesian model averaging (BMA)
Projection

ABSTRACT

As the most excellent indicator for hydrological cycle and a central link to water-balance calculations, the reference evapotranspiration (ET_0) is of increasing importance in assessing the potential impacts of climate change on hydrology and water resources systems since the climate change has been becoming more pronounced. In this study, we conduct an investigation on the spatial and temporal changes in ET_0 of the Haihe River Basin in present and future stages. The ET_0 in the past five decades (1961–2010) are calculated by the Penman–Monteith method with historical climatic variables in 40 sites while the ET_0 estimation for the future period of 2011–2099 is based on the related climatic variables projected by Coupled General Circulation Model (CGCM) multimodel ensemble projections in Phase 3 of the Coupled Model Intercomparison Project (CMIP3) using the Bayesian Model Average (BMA) approach. Results can be summarized for the present and future as follows. (1) No coherent spatial patterns in ET_0 changes are seen in the whole basin. Half of the stations distributed mainly in the eastern and southeastern plain regions present significant negative trends, while only 3 stations in the western mountainous and plateau basin show significant positive trends. Radiation is mainly responsible for the ET_0 change in the southern and eastern basin, whereas relative humidity and wind speed are the leading factors in the eastern coastal and north parts. (2) BMA ensemble method is competent to produce lower bias in comparison with other common methods in this basin. Future spatiotemporal ET_0 pattern analysis by means of the BMA method based on the ensembles of four CGCMs suggested that although the spatial patterns under three scenarios are different in the forthcoming two decades, generally increasing trends can be found in the 21st century, which is mainly attributed to the significant increasing temperature. In addition, the implication of future ET_0 change in agriculture and local water resources is discussed as an extension of this work. The results can provide beneficial reference and comprehensive information to understand the impact of climate change on the future water balance and improve the regional strategy for water resource and eco-environment management in the Haihe River Basin.

1. Introduction

Research and investigation aimed at assessing the hydrological consequence of climate change have mushroomed in recent years, and climate-induced hydrological and subsequent water resources issues have been paid great attention by policymakers and stakeholders in both the developing and developed countries (Jhajharia et al., 2011). As the only hydrological variable that connects water balance and energy balance (Xu et al., 2006; Zhang et al., 2011), evapotranspiration is considered as one of the most excellent indicators to reflect the effect of climate change (Cannarozzo et al., 2006; Xu et al., 2006). Moreover, evapotranspiration is also involved in the management of farmland and pasture irrigation, maintenance of forest and oasis ecosystems, sustainable water supply for industrial and domestic demand, and environmental and ecological water requirement estimation as an indispensable component (Song et al., 2007; Zhang et al., 2009; Zuo et al., 2011). In these contexts, identifying the spatial and temporal patterns of evapotranspiration variations is of great significance for not only in-depth understanding of the hydrological mechanisms responding to climate change but also water resources planning and management. A number of studies have thus been

* Corresponding author at: State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China. Tel.: +86 25 83786982; fax: +86 25 83786606.
E-mail addresses: wangweiguang006@126.com, wangweiguang006@gmail.com (W. Wang).

0921-8181/$ – see front matter. Crown Copyright © 2014 Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.gloplacha.2014.01.004

conducted to address the spatiotemporal trends of evapotranspiration in different regions over the world (e.g., Liu et al., 2004; Xu et al., 2006; McVicar et al., 2007; Zhang et al., 2011; Wang et al., 2011; Dinpashoh et al., 2011; Zhang et al., 2012; Yang and Yang, 2012; Li et al., 2013). In contrast to the expectation that global warming would increase evapotranspiration, a widespread decline in pan evaporation and/or potential or reference evapotranspiration has been observed or detected over the past decades in many regions of the world, which is known as the "evaporation paradox" (Roderick and Farquhar, 2002). The decrease in diurnal temperature ranges (e.g., Peterson et al., 1995), the decrease in global solar irradiance caused by changes in cloudiness or aerosol (e.g., Roderick and Farquhar, 2002), the decline in wind speed (e.g., Rayner, 2007) and the complementary relationship between actual evapotranspiration and potential evapotranspiration (e.g., Brutsaert and Parlange, 1998; Hobbins et al., 2004; Ramírez et al., 2005) have been used to explain the reason for the decreases in pan evaporation with increases in air temperature.

Reference evapotranspiration (ET_0) is defined as the rate of evapotranspiration from a reference crop being free of water stress and diseases with fixed height and surface resistance (Allen et al., 1998). Expressing the evaporating power demand of the atmosphere at a specific location and time of the year without considering the crop characteristics and soil factors (Allen et al., 1998), ET_0 can be considered as a microclimate parameter and can be computed directly from weather data. Not only in agricultural water scheduling but also in conceptual hydrological modeling, actual evapotranspiration is usually estimated based on ET_0 according to the plant and soil characteristics (Allen et al., 1998; Xu et al., 2006). Therefore, ET_0 and its changing patterns are the most important characteristics to be considered in scheduling run times of irrigation system, preparing input data to hydrological models of water balance research, evaluating hydrological effect of climatic change, etc. (Allen et al., 1998; Hobbins et al., 2001; Xu and Singh, 2005; Xu et al., 2006; Gong et al., 2006). In recent years, from the global perspective, a considerable attention has been paid to examine the potential impact of climate change on ET_0, which is reflected by explosive growth of studies on this topic (e.g., Goyal, 2004; Xu et al., 2006; Chen et al., 2006; McVicar et al., 2007; Burn and Hesch, 2007; Zhang et al., 2007; Bandyopadhyay et al., 2009; Liang et al., 2010; Liu et al., 2010; Dinpashoh et al., 2011; Tabari et al., 2011; Jhajharia et al., 2011; Wang et al., 2011, 2012a; Zuo et al., 2011; Yang et al., 2011b; Papaioannou et al., 2011). In fact, as the basis of sustainable and equitable water management, reliable estimation of the terrestrial water balance is of increasing importance in assessing the effects of climate change which becomes more pronounced (Bates et al., 2008). In consequence, being the central to water balance calculations, future ET_0 projections using climate models are more highly demanded than historical ET_0 analysis. Substantial progress in both global and regional modeling at medium to high resolution as well as the downscaling methods allowed an increasing number of studies on modeling effect of climate change. With the support of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007), over 20 modeling groups around the world conducted climate change simulation by different Coupled General Circulation Models (CGCMs) (IPCC, 2007), which is also known as Phase 3 of the Coupled Model Intercomparison Project (CMIP-3) (Meehl et al., 2007) ensemble simulations. Some models can fully provide the relevant meteorological variables driving the ET_0 calculations such as Penman–Monteith (P–M) method, offering opportunities for us to conduct the multi-model ensemble analysis of the simulation and projection of future ET_0. For example, Kingston et al. (2009) estimate potential evapotranspiration response to changing climate by six potential evapotranspiration methods based on climatic data derived from the ensembles of five different CMIP-3 GCMs and discussed the uncertainties in the estimation of potential evapotranspiration under climate change.

Meanwhile, the Bayesian model averaging (BMA) method is proposed for model evaluation and multi-model averaging with a systematic consideration of model uncertainty (Min et al., 2004, 2005; Min and Hense, 2006). As a way to combine different models, BMA is rather a promising method for calibrating multimodel ensemble modeling and forecasting in climatic impact research. BMA is also a method of combining forecasts from different sources into a consensus probability density function (PDF), an ensemble analog to consensus forecasting methods applied to deterministic forecasts from different sources (Vislocky and Fritsch, 1995; Krishnamurti et al., 1999; Yang et al., 2011a). BMA naturally applies ensemble system to a set of discrete models (such as the Canadian ensemble system). The weighted average of individual forecast PDFs constitutes the overall forecast PDF in BMA. As the estimated posterior model probabilities, the weights can reflect the forecast skill of individual models in the training period and provide a basis for selecting ensemble members (Raftery et al., 2005; Wilson et al., 2007). In the present context, as the computational cost of running ensembles is more affordable, the BMA can be a valuable strategy and is widely employed in climate change studies including detection, attribution and climate model evaluation (Min and Hense, 2006) as well as in future projections of climate extremes (Yang et al., 2011a).

Given the strong likelihood of future change in the global hydrological cycle (Bates et al., 2008), there is a growing need to investigate and understand the response of ET_0 to climate change in the future based on the state-of-art climate models and ensemble approaches in individual and typical regions. There is, however, scarce literature regarding changes in ET_0 in the future under the global warming conditions. Even in the available literature on climate impact research involving the ET_0 change in the future (e.g., Chattopadhyay and Hulme, 1997; Moratiel et al., 2011), in-depth studies concerning ET_0 responses to projected future change in climate are still inadequate. Most of the aforementioned efforts focused only on the ET_0 change based on individual GCMs or under given constant increases in CO_2 concentrations. To the best of our knowledge, reports in constructing reliable scenarios of future ET_0 are very limited so far, especially in non-humid zones, motivating our present research. This study addresses this research gap by offering the most comprehensive analysis of future ET_0 in the Haihe River Basin in North China based on CGCM multi-model ensemble projections with BMA approach. This paper tends to: (1) investigate the spatial and temporal inter-annual changes in ET_0 estimated by the P–M methods as well as the contributing factors to this change in the Haihe River Basin using the latest observed meteorological variables in the past five decades (1961–2010); and (2) construct scenarios of ET_0 using multi-model ensemble projections (2011–2100) over this basin provided by CMIP-3 based on the BMA method. Furthermore, the implication of future ET_0 change for local water resources utilization and drought variations in the basin will also be discussed as an extension of this paper. The results are expected to contribute to a better understanding of spatial and temporal patterns in future ET_0 changes, which will be beneficial to identify different regional hydrological and water resources responses to global change and thus to formulate regional strategies against the potential menaces of climate change.

2. Study region and data processing

2.1. Study region

The Haihe River Basin, one of the major basins in China and dominated by semi-arid climate, is selected in this study to demonstrate the regional response of ET_0 to global climate changes in non-humid zones. Located in North China (between 112°E–120°E and 35°N–43°N), the Haihe River flows through many major cities including Beijing and Tianjin and has a total drainage area of 318,000 km^2 (Fig. 1). The Haihe River Basin is composed of three principal sub-basins named Luanhe, Haihe and Tuhaimajiahe. Plateaus and mountains comprise 189,000 km^2 accounting for nearly 60% of the total area and the plains cover 129,000 km^2 accounting for about 40%. The climate of the Haihe River Basin is of the temperate continental monsoon type with summer rainfall in June to August. The mean annual precipitation is 509.9 mm and the mean annual runoff