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Sensitivity of terrestrial water and carbon fluxes to climate variability in semi-humid basins of Haihe River, China

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ABSTRACT

Inter-annual climate variability dominates the evolution of eco-hydrological processes over the water limited basins. Haihe Basin in semi-humid northern China is under significant climate change and serious human disturbance during the recent decades. Integrated with NASA Terra-Modis remote sensing LAI data products, the VIP eco-hydrological model is used to predict the spatiotemporal variations of evapotranspiration (ET) and vegetation gross primary production (GPP) over two catchments of Haihe River branches from 2000 to 2013. Along with precipitation increasing, average annual ET and GPP are significantly increasing. The trends are more distinct over the mountainous upstream areas. The inter-annual variations of ET and GPP are highly correlated with the 12-month SPI (Standardized Precipitation Index), while the monthly GPP is related clearly with 3-month SPI. Sensitivity analysis shows that there are remarkable differences in the elasticity coefficients of both ET and GPP to the climatic factors. It is found that precipitation, solar radiation and leaf area index are the most sensitive factors to ET and GPP in the study basin. The results are helpful to understand the catchment eco-hydrological mechanisms and their responses to climate change.

1. Introduction

Due to insufficient precipitation, water limitation is affecting the agricultural and natural ecosystems sustainability in the North China Plain, where stream flow from the upstream mountainous area is transferred to the downstream plains for cropland irrigation, environmental and industrial uses, and domestic utilities, etc. Agricultural production consumes as high as 60–70% of the available water resources here, most of which return to the atmosphere by evapotranspiration (ET). Water vapor loss from the terrestrial ecosystems to the atmosphere is by three ways, one is from the plant leaf stomata as transpiration, the others are from the wet leaves and soil surface as evaporation. Generally canopy transpiration is the principal component of evapotranspiration and dominates the spatial variability of evapotranspiration, which is regulated by soil moisture and meteorological variables through stimulating leaf stomata openness/closure (Buckley and Mott, 2013). Commensurated with the social and economic development, more water volume is required for non-agricultural purposes, which will inevitably exacerbate conflicts and competition for water use rights in the region. Further, climate variation/change has been revealed to increase security risks with respect to water supply and food production (IPCC 5). Hence, understanding the eco-hydrological processes and their associated impacts on water budget components is essential for such aspects as drought detection, hydrological prediction, crop irrigation schedule, assessments of crop productivity and water use intervention, which is indispensable for practices of integrated catchment management and water resources assignment (Mo et al., 2013; Glenn et al., 2010).

Ecosystem water and carbon fluxes are considerably affected by climate variability through a set of coupled physical and physiological processes. Climate variability is referred to as alterations in precipitation frequency and amounts, changes in the diurnal patterns of temperature and humidity, changes in wind speed and the variability of downward radiation, among others (Paschalis et al., 2015). These changes at sub-daily to seasonal scales have been found to exert significant impacts on the ecological and hydrological processes, which interact crossing scales in complex ways. Notwithstanding, ecosystem resilience may maintain the plant water use efficiency in a conservative way, which has evolved to

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stabilize the ecosystem functions exposed to climate variations (Ponce Campos et al., 2013), via modifying vegetation dynamics (phenology, photosynthesis, canopy density, etc.) under regulation of soil moisture in the root zone (Brown et al., 2010; Baker et al., 2010; Forzieri et al., 2011; Saunders et al., 2014; Mo et al., 2014). At large spatial scales, climate controls the evolution of vegetation productivity, such as Yu et al. (2013) presented that near 80% of spatial variations of terrestrial ecosystem primary productivity in China may be explained by mean annual precipitation and temperature; Nayak et al. (2012) reported that inter-annual variability of NPP exhibited strong positive coherence with the variability of precipitation over the continental India. Therefore, the relationship of inter-annual variations of vegetation productivity is considered to be significant in water limited regions. On the other hand, vegetation dynamics also exert significant impacts on the hydrological processes, such as transpiration, stream and groundwater recharge (Mo et al., 2004; Raupach et al., 2013; Chen et al., 2014). Plants usually respond more rapidly to meteorological drought than river discharge and groundwater regime do (Sawada et al., 2014). Lei et al. (2014) reported that the decreasing trend of runoff may be remarkably underestimated in the hydrological simulations if the vegetation dynamics (especial for phenology) are not taken into account over the water-limited basins. On the other hand, the vegetation responses to climate variability are temporal scale dependent. Vegetation productivity is significantly related to the inter-annual variability in precipitation, especially for water-limited environment (Forzieri et al.,2014), whose variations are also highly correlated with the spells of favorable meteorological condition (Fatichi and Ivanov, 2014), exceptional or extreme inter-annual climatic events (Saunders et al., 2014).

For research and practical purposes, a number of reliable methods and models have been developed to measure or predict terrestrial water vapor and carbon fluxes at local and field scales (*e.g.*, Liu et al., 2013). Due to tremendous heterogeneity in vegetation conditions, soil texture, geomorphology, hydrologic and climate forces, *etc.*, scaling up the local measurements to a large scale is still confronted with significant uncertainty (Sheffield et al., 2010; Mo et al., 2014). As the advent of remote sensing (RS) and GIS technologies, remotely sensed information from the Earth orbit satellites is broadly explored to retrieve the land surface characteristics. For example, visible and near-infrared spectral reflectance and their combinations (referred to as vegetation indices) are capable of diagnosing the spatiotemporal variations of vegetation cover fraction, leaf area index, absorption fraction of photosynthetically active radiation (PAR) by canopy (f_{par}), foliage chlorophyll content, crop coefficient, *etc.* (*e.g.*, Glenn et al., 2010). Therefore, the process-based land surface models or eco-hydrological dynamic models that integrate remotely sensed vegetation index/leaf area index products are useful tools to bridge the spatiotemporal gap from local patch to basin and regional scales. In the simulation, both soil moisture data retrieved from microwave radiance (Bastiaanssen et al., 2012) and soil thermal inertia with daily temperature amplitude (García et al., 2013) are also introduced to account for the plant water stresses. These modelling techniques and skills are broadly used to simulate the eco-hydrological evolution in recent decades (Mo et al., 2014; Mo et al., 2005; Fisher et al., 2008; Ryu et al., 2011; Bastiaanssen et al., 2012; Cai et al., 2014).

The seasonal evapotranspiration estimates from a physical model with remote sensing information are usually verified by in situ measurements and basin water balance, etc. The accuracies of predicted water vapor fluxes are illustrated to be reliable at annual and seasonal scales with 10–30% relative errors and less than 30 W m^{-2} of RMSE (Root Mean Square Error) and 30% MRE (Mean Relative Error) at daily scale (Bastiaanssen et al., 2012; Jin et al., 2011; Wang and Liang, 2008; Mu et al., 2011; Fisher et al., 2008; Cleugh et al., 2007; Jia et al., 2012). The uncertainties are principally related with the biophysical controls of moisture stress, vegetation index, bulk canopy resistance (Polhamus et al., 2013) and spatial interpolation of atmospheric forces, which may give rise to remarkably different patterns and inter-annual trends of simulated water and carbon fluxes (Chen et al., 2014).

Accurate estimation of water vapor and carbon fluxes is important to evaluate the eco-hydrological responses to climate variability and land use/cover changes in the semi-humid basins, where plants are sensitive to environmental modifications. Haihe River in the northern China is an example. It is located between 112.0°E–119.8°E and 35.0°–42.8°N and covers 318,200 km^2, and supports 10% of the population with only 1.5% of the water resources of the country. Over the basin, the continental monsoon climate is prevailing with hot and wet weather in summer and cold and dry weather in winter seasons. In the recent decades, climate variation/change and human activities (land use change and irrigation) have led to unwavering decline of stream runoff, which accentuates the shortages of water resources in the downstream farmlands (Yang and Tian, 2009; Bao et al., 2012). Here two conterminous catchments, namely Ziya and Daqing in the south of Haihe River Basin are focused, which consist of upland mountains and hilly areas and lowland plains. In the two basins, human activities have considerably modified the hydrological processes associated with land use changes, agricultural managements as well as domestic and industrial water utilities in the mid and low reaches. The purpose of this paper is to investigate the evolutions of eco-hydrological processes at basin scale in the recent decade. By using the VIP eco-hydrological dynamic model integrated with the Terra-Modis remotely sensed vegetation products at 1 km resolution from 2000 to 2013, the spatial patterns of vegetation primary productivity and water consumption are explored. The following issues are revealed: (1) Trends and variability of evapotranspiration (ET) and vegetation gross primary productivity (GPP) in the recent decade; (2) Effects of droughts on ET and GPP; (3) Sensitivities of ET and GPP to inter-annual climate variability.

2. Materials and methods

2.1. Sites and data

There are two main branches (Ziya River and Daqing River, respectively) of Haihe River in the study domain with an area of 81,600 km^2 as shown in Fig. 1. Some large storage reservoirs have been built in the upper and mid reaches. The upper streams are stemmed from the Taihang Mountains, and the down streams are extended to the North China Plain. As the largest water body and wetland of Haihe River basin, the Baiyangdian Lake is located in the downstream of Daqing River. Over the basins, the multi-year mean air temperature is about 10 °C. With most of the precipitation events occurring in summer season and fluctuating inter-annually, the mean precipitation is about 500 mm per year. As shown in Fig. 1b, land cover/use is classified into 10 classes in the catchments, interpreted from Landsat-TM images (http://www.resdc.cn). Fractions of farmland, forest, woody grassland and water body are 48, 24, 26 and 2% respectively. In farmland the prevailing cropping systems are winter wheat-summer maize rotation in the piedmont plain and single autumn harvest crops (spring maize, sorghum and millet) in the western valleys. Due to insufficient precipitation in springtime and early summer, irrigation is practiced to crops in farmland with water supply facilities.

The 8-day maximum composite leaf area index from Terra – MODIS products (MOD15A2) are utilized (http://modis.gsfc.nasa.gov) to retrieve the land surface characteristics and canopy phenology. According to the MOD15A2 quality assessment scheme (Myneni et al., 2002), LAI values retrieved by Radiation Transfer