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Validating the Runoff from the PRECIS Model Using a Large-Scale Routing Model

CAO Lijuan*[1,5] (曹丽娟), DONG Wenjie[2] (董文杰), XU Yinlong[3] (许吟隆),
ZHANG Yong[1,2,3] (张 勇), and Michael SPARROW[4]

[1] *Key Laboratory of Regional Climate-Environment for Temperate East Asia,*
Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

[2] *National Climate Center, China Meteorological Administration, Beijing* 100081

[3] *Institute of Environment and Sustainable Development in Agriculture,*
Chinese Academy of Agricultural Sciences, Beijing 100081

[4] *International CLIVAR Project Office, National Oceanography Centre, Southampton, UK*

[5] *Graduate University of Chinese Academy of Sciences, Beijing,* 100049

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ABSTRACT

The streamflow over the Yellow River basin is simulated using the PRECIS (Providing REgional Climates for Impacts Studies) regional climate model driven by 15-year (1979–1993) ECMWF reanalysis data as the initial and lateral boundary conditions and an off-line large-scale routing model (LRM). The LRM uses physical catchment and river channel information and allows streamflow to be predicted for large continental rivers with a $1^\circ \times 1^\circ$ spatial resolution. The results show that the PRECIS model can reproduce the general southeast to northwest gradient distribution of the precipitation over the Yellow River basin. The PRECIS-LRM model combination has the capability to simulate the seasonal and annual streamflow over the Yellow River basin. The simulated streamflow is generally coincident with the naturalized streamflow both in timing and in magnitude.

Key words: regional climate model, large-scale routing model, model validation, runoff, the Yellow River

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1. Introduction

It has been widely accepted that modeling land surface processes plays an important role not only in large-scale atmospheric and global climate models (GCMs), but also in regional climate models (RCMs). Uncertainty in land-surface processes coupled with uncertainty in parameter data limits the confidence we have in the simulated regional impact studies. River runoff is one of the most important land-surface processes used in evaluating the surface water budgets. Streamflow is a temporally-lagged, spatial integral of river runoff over a river basin. However, most land-surface schemes in GCMs or RCMs simulate runoff but not streamflow. For most climate models, runoff is simply an excess of precipitation over evapotranspiration and local moisture storage change that combines various terms (including, for example, fluxes to or from groundwater, direct surface runoff, and baseflow) that may eventually be evidenced as streamflow. Therefore, a routing model is needed to translate model-simulated runoff into streamflow (Lohmann et al., 1998; Xu et al., 2005).

Realistic routing of river flows is important for several reasons. For instance, river routing in climate models provides a basis for comparing and validating GCM or RCM estimates of runoff with the observed river hydrograph data. Provided GCM or RCM esti-

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*Corresponding author: CAO Lijuan, caolj@tea.ac.cn

mates of precipitation and other atmospheric variables are realistic, estimates of river runoff can be used to assess the adequacy of its land surface parameterization scheme (Liston et al., 1994; Nijssen et al., 1997; Wood et al., 1998). Previous literature has described the use of simple river routing schemes to predict the long-term mean runoff from major rivers around the world (Russel and Miller, 1990; Dümenil and Todini, 1992; Kuhl and Miller, 1992; Liston et al., 1994; Miller et al., 1994; Sausen et al., 1994), in which the simulated runoff of GCMs is used as the input to the routing models. Because the resolution of GCMs is too coarse to accurately reproduce many regional characteristics, this typically results in large errors in the predictions. Using a regional climate model and an off-line large-scale routing model to simulate the streamflow is a way of providing improved predictions.

The Yellow River has drawn the attention of a growing number of scientists since it is well known for its large drainage area, with high sand content, frequent floods, unique channel characteristics in the lower reaches, and limited water resources (Fu et al., 2004). A large number of studies have been carried out on the Yellow River by analyzing observational data or downscaling of modeled climate variables in the basin as well as using macro-scale hydrological models such as the Variable Infiltration Capacity (VIC) model to investigate hydroclimatic trends due to climate change and other factors over a long time period (e.g., Zhang et al., 2003; Fu et al., 2004; Hao et al., 2004; Lan et al., 2004; Liu and Zheng, 2004; Xia et al., 2004; Xie et al., 2004; Xu, 2005).

This study uses PRECIS (Providing REgional Climates for Impacts Studies) and a LRM (a large-scale routing model) to investigate the streamflow changes during 1979–1993 over the Yellow River basin. The aim of this research is to validate the ability of the PRECIS model to reproduce the hydrological processes so that the simulated results can better be used in hydrological impact studies. The paper is organized as follows: section 2 briefly describes the models used in this study, section 3 describes the basin and experiment design, section 4 discusses the results, and finally the conclusions are given in section 5.

2. Model description

The PRECIS model, a regional climate model system developed by the Hadley Centre, can be run over any area of the globe to provide regional climate information for impacts studies (Jones et al., 2004). It was introduced into China in 2003 to develop the high-resolution SRES (Special Report on Emissions Scenarios) climate change scenarios. It uses relatively high horizontal resolution ($0.44° \times 0.44°$), which allows it to be run at reasonable computational cost over a domain covering most of East Asia. The model has 19 vertical levels in the atmosphere and runs at a time step of five minutes. Xu et al. (2006) and Zhang et al. (2006, 2007) employed PRECIS to simulate the baseline (1961–1990) mean climate and extreme climate events for evaluation of the model's capacity to simulate present climate and analyze the future change responses of mean climate and extreme climate events in the time-slice of 2071–2100 under the IPCC SRES B2 scenario over China relative to a baseline average.

The land-surface scheme employed in the PRECIS model is the MOSES (Meteorological Office Surface Exchange Scheme), which is one of the land-surface schemes (LSSs) that participated in the Project for Inter-comparison of Land-surface Parameterizations (PILPS) Phase 2(e) experiment, and showed good skill in land-surface simulation (Bowling et al., 2003; Nijssen et al., 2003). The MOSES uses four soil layers in the vertical with depths chosen to capture important soil temperature cycles. The scheme describes two components of runoff: surface runoff and subsurface runoff. As precipitation hits the canopy the remainder of the canopy interception falls to the surface. This canopy throughfall infiltrates the soil at a rate of saturated hydraulic conductivity multiplied by an enhancement factor. Surface runoff is generated when the local throughfall rate exceeds the infiltration rate. Subsurface runoff is mainly affected by soil moisture. Drainage through the soil is calculated using a discretized version of the Richards' equations with four soil layers (thicknesses: 0.1, 0.25, 0.65, 2.0 m). Hydraulic conductivity and suction are calculated using Clapp-Hornberger characteristic curves (Gedney and Cox, 2003). A detailed description of the MOSES can be found in Cox et al. (1999) and Essery et al. (2001, 2003).

The LRM model, which is based on assumptions of linearity and time invariance, comes from the Department of Hydrological Sciences, University of Arizona. The runoff reaching the outlet of a grid box and the transport of water through the river network are calculated in the routing model. It is assumed that water can leave a grid cell only in the direction of one of its eight neighboring grid cells. The runoff is then combined with the river discharge and routed downstream. A simple baseflow separation technique is used to account for the different timing response of surface and subsurface runoff, which is well established in the literature (Linsley et al., 1975). The surface runoff calculation is represented based on the concept of the unit hydrograph (UH) in each grid cell. Once the water is transported out of the grid cell, it is further routed

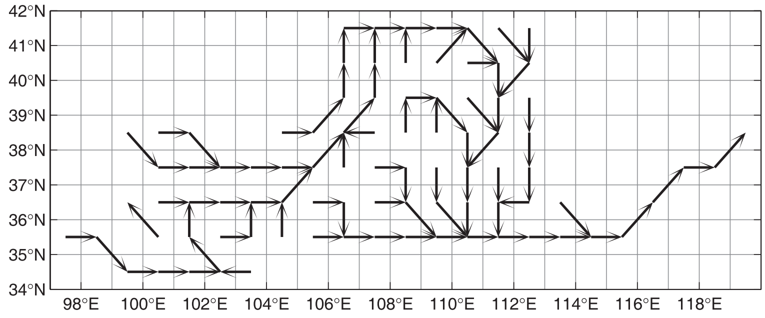

Fig. 1. The 1° × 1° schematic river network for the Yellow River basin.

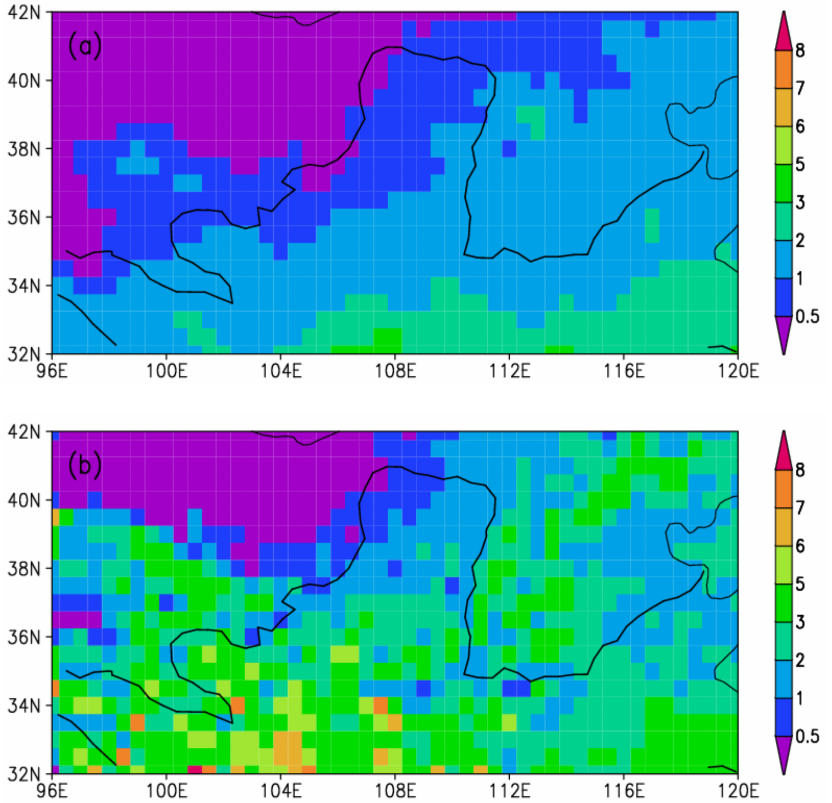

Fig. 2. The (a) observed and (b) simulated annual mean precipitation (mm d^{-1}) for the Yellow River basin.

through the stream network (Fig. 1). River routing is calculated with the linearized Saint-Venant equation (Lettnmaier and Wood, 1993):

$$\frac{\partial Q}{\partial t} = D\frac{\partial^2 Q}{\partial x^2} - C\frac{\partial Q}{\partial x} \ .$$

Typical wave velocities, C, range between 0.8 m s^{-1} and 1.5 m s^{-1} and diffusivities, D, range between 600 m^2 s^{-1} and 2000 m^2 s^{-1}. The parameters C and D can be found from measurements or by rough estimation from the geographical data of the riverbed. The equation is solved with convolution integrals of its impulse-response (or Green's) function (Todini, 1991; Lohmann et al., 1996).

3. Domain and methods

The Yellow River, which is the second longest river in China, lies in the region 32°–42°N and 96°–119°E. The climate ranges from humid and semi-humid conditions in the eastern part of the basin to semi-arid and arid conditions in the western part. Precipitation in the basin falls mainly during the summer, particularly during the summer monsoon. Climatically, the

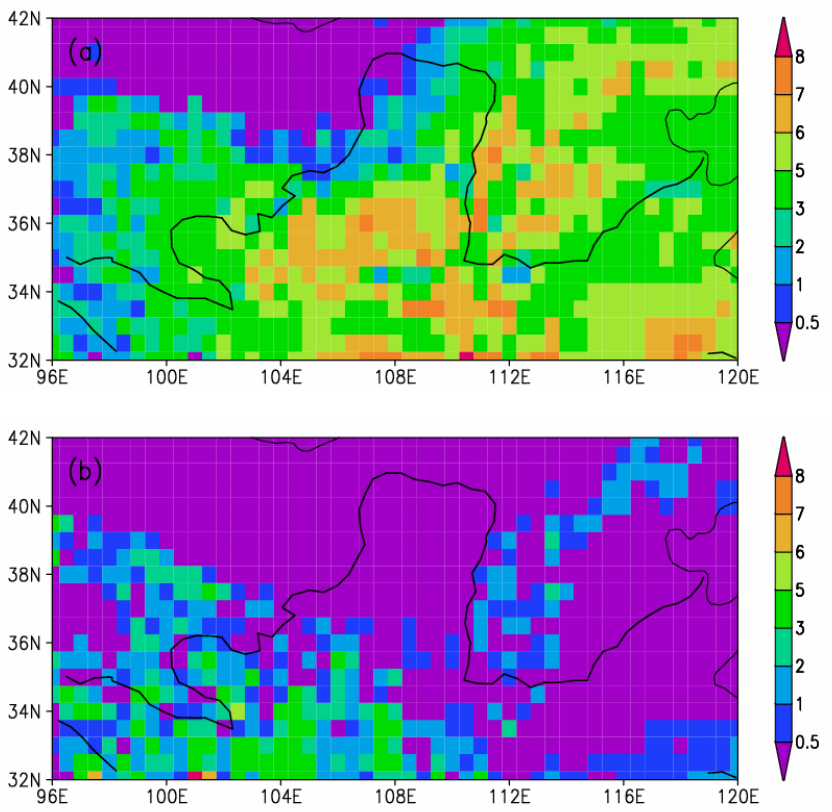

Fig. 3. (a) The simulated annual mean evapotranspiration and (b) total runoff (mm d^{-1}) for the Yellow River basin.

basin mostly lies in semi-arid and arid regions with high evaporation and low runoff. The annual mean precipitation of the basin is only 475.9 mm, and annual mean evapotranspiration reaches 388.3 mm. The runoff varies significantly in time and space with high flow occurring in the summer season and fluctuates greatly from year to year (Xia et al., 2004).

In this study, the initial and lateral boundary conditions for PRECIS are obtained from 15-year (1979–1993) ECMWF (the European Centre for Medium-Range Weather Forecasts) reanalysis data. The simulated hydrological variables of PRECIS include precipitation, evapotranspiration, surface and subsurface runoff in hourly, daily, monthly, seasonally and yearly time steps. The simulated surface and subsurface runoff results in each grid cell are considered as being distributed uniformly over the area of the grid cell. The hydrographs produced for each grid cell are then routed to the basin outlet using the LRM model.

The daily surface runoff and subsurface runoff from each grid cell calculated by PRECIS for the time-slice 1979–1993 was interpolated to the 1° × 1° horizontal grid and then used to drive the LRM. The data for driving the LRM also includes the latitude and longitude of the hydrological stations, the catchment area, the river network, and C, D, and UH of each grid cell. The integral step size of the LRM is 60 minutes. The channel network linking the individual grid cells is schematized at the 1° grid scale by connecting the centers of the grid cells following the main direction of flow. The schematically simplified stream network can be seen in Fig. 1. Once the water is transported out of the grid cell, it is further routed through the stream network. Flow velocities in the routing model were adjusted manually, resulting in values from 1.0 m s^{-1} to 2.0 m s^{-1} for the Yellow River. These values do not represent actual channel velocities, since the travel distance between two grid cells is taken as the distance between their centers. The numbers therefore reflect effective flow velocities. They are comparable to the values used for a similar purpose by Miller et al. (1994).

Because macro-scale hydrological models or land-surface schemes are usually structured to simulate naturalized streamflow (the discharge pattern of many large rivers is regulated by storage in artificial reservoirs, diversions or water withdrawals), naturalized river flows are used in this analysis for comparison with the simulated streamflow. These naturalized streamflows are based on observed river flows but have the agricultural, industrial, urban water consumption and most of the effects of reservoirs and diversions removed (Li and Yang, 2004).

4. Results

The simulated results for the Yellow River are presented in this section. The results generally take one of two forms: maps of the distribution of hydrological variables, such as annual mean precipitation, evapotranspiration and runoff, and monthly time series of such quantities as streamflow at selected locations.

Figure 2 shows the observed and simulated spatial pattern of annual mean precipitation (averaged for the period 1979–1993) over the Yellow River basin (the observational data come from the China Meteorological Administration). It shows that the PRECIS model has reproduced the degression of the precipitation belt from the southeast to northwest over the Yellow River basin. However, the enhancement of the topographic precipitation in PRECIS is caused by stronger vertical ascent due to the dynamical effects of higher resolution (Jones et al., 1995). It shows that the simulated precipitation is higher than observations over mountainous areas such as the eastern edge of the Qinghai-Tibetan Plateau and Qinling and Taihang Mountains, where the excessive accumulated precipitation occurs at steep orography. PRECIS needs to be improved, but this also may reflect an under-representation of the fine-scale signal in the observed data and does not necessarily indicate low skill in the PRECIS fine-sale component.

Figure 3 shows the simulated spatial pattern of annual average evapotranspiration and runoff (averaged for the period 1979–1993) over the Yellow River basin. Both the evapotranspiration and runoff climatology have a general east-west and south-north gradient. The total moisture flux of evapotranspiration is made up of evaporation from the canopy store, transpiration by vegetation, bare soil evaporation and sublimation from the snow surface (Cox et al., 1999). Evapotranspiration is one of the most important processes of the hydrologic cycle and accounts for 80%–85% of the annual precipitation in the Yellow River basin. The evapotranspiration values are found to be large (Fig. 3) in the whole region. It ranges from below 0.5 mm d^{-1} in the northwest to 7 mm d^{-1} in the central and southern parts of the basin, with the highest value occurring in the mountainous area in the south of the Yellow River basin, where the amount of precipitation is large and the temperature relatively high. The lowest evapotranspiration occurs in the northwest desert area, which is a region that suffers from a lack of water resources. The runoff ranges from below 0.5 mm d^{-1} in the north of the basin to over 3 mm d^{-1} in the south of the basin, with the highest runoff occurring in the southern mountainous area of the basin, which is similar to the precipitation climatology pattern.

Figure 4 shows the simulated monthly mean streamflow in comparison to naturalized streamflow for four hydrological stations over the Yellow River from 1 January 1980 to 31 December 1993. The four stations are distributed over different reaches of the Yellow River and produced different mean streamflow patterns. However, in general the maximum streamflow occurs during the summer period from June to October, and the simulated streamflow is similar to the naturalized streamflow both in timing and in magnitude. During the winter and spring periods in most of the experiment years the streamflow is less than 1000 $\mathrm{m}^3\ \mathrm{s}^{-1}$. From Fig. 4 it can be seen that, except for 1987 and 1993, there is a distinct decrease both in naturalized and simulated streamflow in August or September. The reason is probably due to the larger use of water resources during the summer months. Generally, the simulated results are coincident with the naturalized streamflow, especially in the summer season, the exception being that the spring peak runoff is overestimated.

In all cases, the performance is evaluated using the correlation coefficients between monthly mean simulations and naturalized streamflow. The correlation coefficients of the four stations Lanzhou, Shizuishan, Toudaoguai, and Huayuankou are 0.41, 0.60, 0.70 and 0.77, respectively, which are all above 0.6, except for Lanzhou station, and all are statistically significant at the 1% level. The hydrograph at Lanzhou station shows the poorest fit, both in timing and in magnitude, of all of the four stations, perhaps because this station is in the upper reaches of the Yellow River where the runoff yield is more important than the routing process, and that the topographic precipitation is poorly simulated in the upper reaches of Lanzhou station. The Huayuankou station, which is located in the division of the middle and lower reaches, gets the maximum runoff and has the best simulation results of the four stations.

In order to investigate the bias of the variation between the simulations and observations, the coefficient of variation has been calculated, defined as the ratio of the standard deviation to the mean value (CV, henceforth). The observed monthly variability for Lanzhou, Shizuishan, Toudaoguai, and Huayuankou are 0.738, 0.735, 0.741, and 0.670, respectively, while the simulated variability in streamflow are 0.595, 0.577, 0.591, and 0.657, respectively. The simulated relative variability is generally lower than observations because the model overestimates mean rainfall in most areas, while

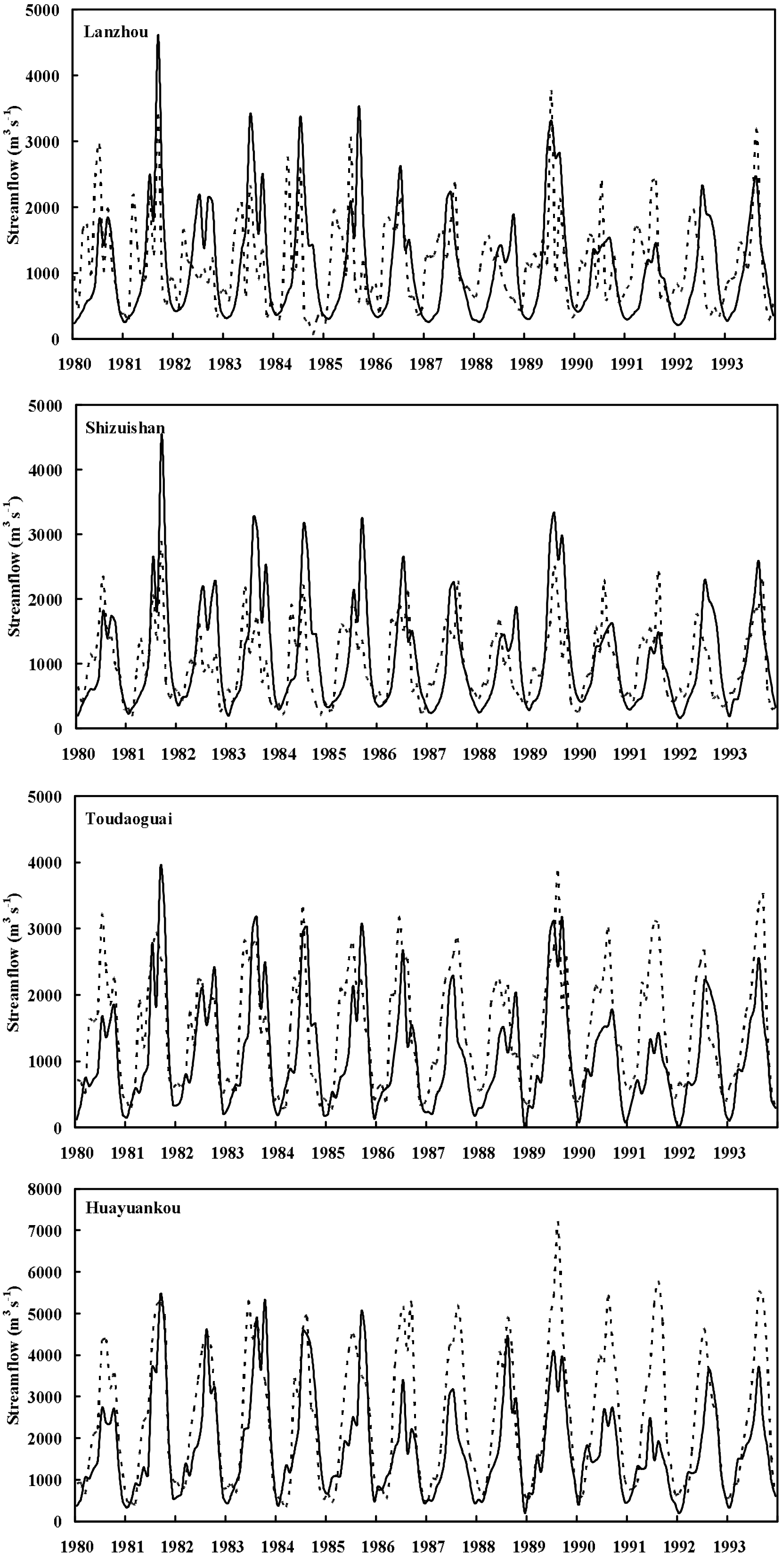

Fig. 4. Time series of naturalized (solid lines) and simulated (dashed lines) monthly mean streamflow.

the precipitation accounts for much of the runoff.

The routing model requires that each grid cell flow is in only one direction, and thus each cell has to be assigned to one sub-basin or another. This can result in relatively large errors for dry sub-basins. In addition, the routing model assumes that each of the calibration locations lies at the edge of a grid cell, which in reality will often not be the case. However, for a site such as Lanzhou, which collects runoff from a large area in the upper reaches of the Yellow River, these edge effects are not so important.

5. Conclusions

In this study, the streamflow over the Yellow River basin has been simulated using the PRECIS regional climate model driven by 15-year (1979–1993) ECMWF reanalysis data as the initial and lateral boundary conditions and an off-line LRM. The study represents an initial application of a LRM for evaluating RCM simulations of land-surface hydrology over the Yellow River basin. The PRECIS model has reproduced the general east-west and south-north spatial distribution of the hydrological variables including precipitation, evapotranspiration and runoff over the Yellow River. The spatial pattern of runoff is consistent with the precipitation climatology. The results indicate that PRECIS can provide detailed regional climate change information that will be useful to impact studies on water resources over the Yellow River basin.

The PRECIS-LRM model combination is capable of reproducing the seasonal hydrograph and annual streamflow over the Yellow River basin in China. The results show that the streamflow is similar in timing and less good in magnitude, between the simulations and the naturalized streamflow. The correlation coefficients were all above 0.6, except for Lanzhou station (0.41), with all statistically significant at the 1% level. The model gave poorer results in Lanzhou station, perhaps because the location is in the upper reaches of the Yellow River where the runoff yield is more important than the routing process, while the topographic precipitation was poorly simulated in the upper reaches of Lanzhou station. Moreover, although the influences of human-induced changes on the naturalized streamflow have been partly removed, there are still some human influences that have not been accounted for (such as land-use change and its hydrological impacts).

The bias is significant in all stations perhaps because the errors from the RCM can be transferred into the LRM. In addition, the resolution of the RCM remains too coarse to correctly simulate convective processes. As computer capabilities increase, it will be possible to produce higher-resolution simulations, which may improve the simulation of convective precipitation. Furthermore the resolution of the LRM is 1° and larger than the resolution of the RCM model which also produces significant errors.

In order to improve the capacity of the PRECIS model to simulate regional climate, especially in China, the water budgets processes in the land-surface schemes need to be further improved. In addition, the parameters in the LRM model need to be adjusted further. In future studies, the fine resolution of the LRM model will be developed to better match the resolution of the regional climate model, which will improve the model results.

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