Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 154 (2016) 687 – 695
Procedia Engineering
www.elsevier.com/locate/procedia

12th International Conference on Hydroinformatics, HIC 2016

Impacts of climate changes on water resources in Yellow River Basin, China

Yongnan Zhu[a, b,]*, Zhaohui Lin[b], Jianhua Wang[a], Yong Zhao[a], Fan He[a]

[a] *State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Institute of Water Resources and Hydropower Research, A-1 Fuxing Road, Haidian District, Beijing 100038, China*
[b] *International Center for Climate and Environment Sciences(ICCES). Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China*

Abstract

This study examined the impacts of future climate changes on water resources and extreme flows in Yellow River Basin (YRB), China, using the Coupled Land surface and Hydrology Model System (CLHMS) driven by the IPCC scenarios RCP 2.6, 4.5 and 8.5. First, the skill of 14 IPCC AR5 GCMS for simulating temporal and spatial temperature and precipitation in Yellow River Basin has been evaluated. Using the bias-corrected result of RCP storylines, the CLHMS model was developed to predict the 21 century climate and water cycle change. All the three simulation results indicate a reduction in water resources. The current situation of water shortage since 1980s will keep continue, the water resources reduction varies between 30 and 24% for RCP 2.6 and 4.5 scenarios. RCP 8.5 scenario simulation shows a decrease of water resources in the early and mid 21th century, but after 2080, with the increase of rainfall, the extreme flood events tends to increase.

Peer-review under responsibility of the organizing committee of HIC 2016

Keywords: Coupled land surface-hydrology model, Water resources, climate change, hydrological process simulation, Yellow River Basin

1. Introduction

The water cycle involves the continuous circulation of water in the Earth-Atmosphere system. It is the linkage

* Corresponding author. Tel.: +86-10-68781370; fax: +86-10-68483367.
E-mail address: zhyn@iwhr.com

Peer-review under responsibility of the organizing committee of HIC 2016
doi:10.1016/j.proeng.2016.07.570

among atmosphere, hydrosphere, biosphere and geosphere. Under the background of global warming, glacial ablation makes sea level rise and land water form change. It is indicated from the statistics of that climate change has already changed water cycle characteristics [1]. Climate change have been widely investigated throughout the world. But how climate change will affect the temporal and spatial distribution of water cycle in the future? This problem has become the key issue of international society [2, 3].

From General Circulation Model (GCMs) to Atmosphere-ocean General Circulation Model (AOGCMs). The scientists focus on the study of the physical process of climate system model to improve the simulation performance. As a powerful tool for climate change research, GCMs allow the simulated climate to adjust changes in climate forcing, it provide a method to reveal the water cycle processes and to predict the trend of future climate change.

The Yellow River (YRB) is located in northern China. It is the second longest river in China and the sixth longest river in the world at the estimated 5464 km. Its total basin area is 0.75 million km^2. Over the past 50 years, the precipitation of YRB presents downward trend, among which, the decreased rainfall in spring and autumn is the most obvious [4]. Meanwhile, the runoff in the basin is obviously decreasing [5]. The contradiction between supply and demand of water resource in YRB is increasingly severe.

This study is intended to estimate the changing trends of water resources in the YRB using a coupled land surface and hydrological model system (CLHMS) driven by the IPCC scenarios RCP 2.6, 4.5 and 8.5. Section 2 briefly describes the model and the YRB. In consideration of the GCMs simulation ability in different areas, firstly the temperature and precipitation simulation capabilities during the 20th century (1962-2005) of 14 GCMs in YRB are examined in section 3. On the basis of that, three different RCP scenarios (RCP2.6, RCP4.5 and RCP8.5) are used to drive the CLHMS model. And the climate and water resources changing trend in the 21st century in the Yellow River Basin are analysed and presented in section 4.

2. Model and Study area

2.1. Model description

The Coupled Land surface and Hydrology Model System (CLHMS) include a large scale land surface model LSX [6] and a fine grid distributed hydrological model HMS. The coupling between the LSX and HMS is based on predicted soil moisture and surface water depth [7]. The land-surface models include two-layer vegetation model, three-layer snow model and six-layer soil model; the hydrological models include terrestrial hydrologic model (THM), groundwater hydrologic model (GHM) and channel ground-water interaction (CGI).

The Parameters in the CLHMS model include soil texture, vegetation type, hydrological parameters and hydrogeological parameters. Soil texture is interpolated with the global dataset of Global Environmental and Ecological Simulation of Interactive System [8], vegetation type is used CLDH data (China Land-use Data for Hundred years) [9] Hydrologic parameters in the basin are developed from the USGS HYDRO1k DEM with ZB algorithm [10]. The hydrogeological parameters such as hydraulic conductivity and porosity are interpolated with the Harmonized World Soil Database [11]. The CLHMS reproduces well the natural hydrological processes, the simulation performances of the water balance and the seasonal and interannual variation of streamflow are already proved in the Yellow River Basin, Huaihe River Basin and Pearl River Basin in China [12-14].

2.2. Study area and data set

The Yellow River Basin (Figure 1) has an east-west extent of about 1900 km, it is located in the north area of East Asian monsoon region. Affected by atmospheric circulation and monsoon circulation, the spatial and temporal climate of the basin varies obviously. The upper reaches of YRB are in the arid and semi-arid area, and the lower reaches are in the semi humid area. The instability East Asian monsoon is also the cause of uneven seasonal distribution of rainfall, more than 50% of annual rainfall accurse form June to September, while the winter and spring are dry. During the last 50 years, the rainfall and runoff in the basin are significantly decreased.

The CMIP5 (Coupled Model Intercomparison Project Phase 5) experiments includes the historical climate simulation experiments for the 20th century and prediction experiments for the 21st century driven by “Representative Concentration Pathways” concentrations [15]. Based on the East Asia gauge-based analysis of daily precipitation data [16], daily temperature CN05 [17] and the historical run’s outputs of 14 CMIP5 GCM models (Table

1), this article investigates the characteristics of precipitation and temperature. The historical experiment of CMIP5 uses the result of experiment result before the Industrial Revolution (PiHistorical run) as the initial field for integrating, all the observed data were used and varied from time changes as the force field, such as greenhouse gas, ozone, aerosol, volcanic activity, solar constant. The simulation period is from 1850 to 2005 and the simulation result indicates the correspondence relationship between the recurring of historical climate and actual calendar. Therefore, it can be compared with the observational data to estimate the simulation capability of the climate system model.

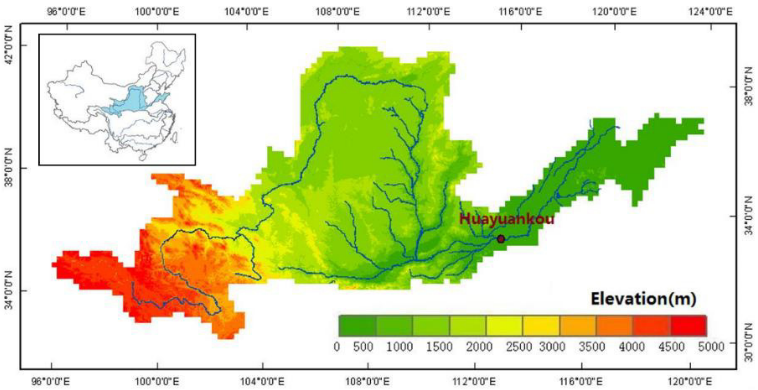

Fig. 1. River systems in Yellow River Basin

The EA precipitation grid point data is provided by NOAA CPC as the daily precipitation data in East Asia (5˚N～60˚N, 65˚～155˚E) for a 28 years based on the observational analysis over 2200 stations. The spatial resolution is 0.5˚×0.5˚ and the time range of the data is from 1978 to 2006. The CN05 temperature data is provided by China Meteorological Administration from 1961 to 2009, the spatial resolution is 0.5°×0.5° with a spatial range of 14.5°N～5.5°N and 69.5°E～40.5°E.

Table 1. CMIP5 GCMs used in this study

No.	Climate Models	Resolution	Institution, Country
1	BCC-CSM1.1	128×64	Beijing Climate Center, China
2	CCSM4	288×194	The National Center for Atmospheric Research(NCAR), USA
3	CESM1-CAM5	288×192	National Science Foundation, Department of Energy, (NCAR),USA
4	CSIRO-MK3.6.0	192×96	Commonwealth Scientific and Industrial Research Organization, Australia
5	CNRM-CM5	256×128	Centre National de Recherches Météorologiques,, France
6	FGOALS-g2	128×60	Institute of Atmospheric Physics(IAP), China
7	GFDL-CM3	144×90	Geophysical Fluid Dynamics Laboratory, USA
8	HadCM3	96×73	Met Office Hadley Centre, UK
9	INM-CM4	180×120	Institute of Numerical Mathematics, Russia
10	IPSL-CM5A-LR	96×96	Institut Pierre Simon Laplace, France
11	MIROC-ESM	128 × 64	JAMSTEC, AORI, NIES, Japan
12	MPI-ESM-LR	192 × 96	Max-Planck Institute, Germany
13	MRI-CGCM	320 × 160	Meteorological Research Institute, Japan
14	NorESM1-M	144 × 96	Norwegian Climate Centre, Norway

3. GCMs simulation abilities in Yellow River Basin

3.1. Methodology

This article selects the observation data and model data form 1962 to 2005 as the reference period. Since the difference of the various data resolution is huge. Therefore, the simulation spatial result of observational data and 14 GCMs is interpolated in the grid point of 1.0°×1.0°. To validate the simulation precision of temperature and precipitation by climate model, the essay uses relative error (MRE), correlation coefficient (CORR) and Nash efficiency coefficient (NSE), among which, MRE mainly reflects the simulation error of climate mean state by the model with the unit %. The smaller the index is, the higher the simulation capability is. CORR reflects the similarity degree of time sequence or space field of observational value and simulation result. NSE reflects the simulation capability of simulation sequence peak value. The closer to 1 the Nash efficiency coefficient is, the higher the model simulation capability is. The formula of the three indexes is as follows:

$$\mathrm{MRE} = \frac{\bar{P}-\bar{O}}{\bar{O}} \times 100\% \quad (1)$$

$$\mathrm{CORR} = \frac{\sum_{i=1}^{N}(P_i-\bar{P})(O_i-\bar{O})}{\left[\sum_{i=1}^{N}(P_i-\bar{P})^2\right]^{0.5}\left[\sum_{i=1}^{N}(O_i-\bar{O})^2\right]^{0.5}} \quad (2)$$

$$\mathrm{NSE} = 1.0 - \frac{\sum_{i=1}^{N}(P_i-O_i)^2}{\sum_{i=1}^{N}(O_i-\bar{O})^2} \quad (3)$$

P_i and O_i are respectively the values at i^{th} period in model simulation and observational sequence, $\overline{P}$ and $\overline{O}$ are respectively the mean value of simulation and observational sequence, and N is the total sample number.

3.2. Simulation performance evaluation for precipitation

Figure 2 gives out the precipitation climate average space distribution chart from 1962 to 2005 in Yellow River basin based on the observation and 14 climate models. Figure 2(a) is the multi-year average climate precipitation chart, which can be indicated that the average precipitation in YRB is 1.33mm/day, presenting the trend of decreasing from southeast coastal to northwest mainland. The precipitation in the lower reach of Yellow River can reach 2mm/day, the majority area in northwest is comparatively drier and the daily precipitation of some areas is even lower than 0.5mm/day. From the perspective of single model, the majority models can simulate the basic characteristics that the precipitation is more in southeast and less in northwest, but some model indicates that the zonal mean precipitation is smaller, such as MRI-CGCM3. Some models simulate more precipitation, such as INM-CM4 and NorESM1-M, while the simulation results of the majority models such as CCM4, CESM-CAM5, CISRO-MK3.6.0 and GFDL-CM3 demonstrate that there is high precipitation value region in the southwest of YRB (Sichuan province), which is inconsistent with the observed value.

Table 2 shows that the majority model overestimates the precipitation in Yellow River, while the simulation error of BCC-CSM1.1, CSIRO-MK3.6.0and MRI-CGCM models on Yellow River Basin are comparatively the smallest, which are respectively 26.0%, 25.7% and -16%. Table 2 also gives the Nash efficiency coefficient in Yellow River, which indicates the simulation capability of the peak value by the selected CMIP5 models. It can be indicated from the table that the simulation difference of peak value by the various models is huge. The Nash efficiency coefficients of CSIRO-MK3.6.0, CNRM-CM5, IPSL-CM5A-LR in Yellow River Basin are all higher than 0.6, among which, the precipitation peak value simulation capability in CNRM-CM5 is the best.

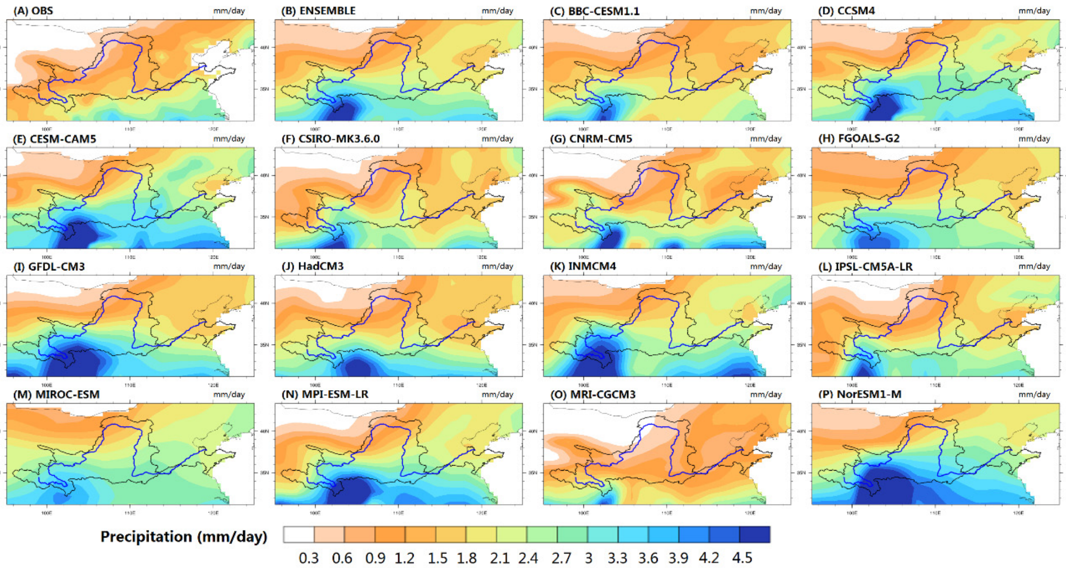

Fig. 2. Precipitation simulation performance of selected CMIP5 models in YRB

3.3. Simulation performance evaluation for temperature

From 1962 to 2005 as the baseline period, the observed mean annual temperature of the Yellow River Basin is 6.53℃. In view of the average temperature of the region, we can see from table 2 that all the 14 CMIP 5 models have a high simulation capacity of air temperature in YRB. The relative errors of CCSM4, CESM1-CAM5, MIROC-ESM and MPI-ESM-LR are small than 1℃. Table 2 also gives the correlation coefficient and Nash efficiency coefficient of the 14 models. To view the result as a whole, the simulation ability of different GCMs to the temperature of YRB is obviously better than that of precipitation. The correlation coefficients of all the 14 models are higher than 0.98, and the Nash efficiencies are between 0.81 and 0.97. Considering the spatial and time distribution of temperature, CCSM4, CESM1-CAM5, CNRM-CM5, GFDL-CM3, HadCM3, IPSL-CM5A-LR, MIROC-ESM, MPI-ESM-LR have a better simulation capability.

Table 2. Comparison of precipitation, temperature with observation in YRB

No.	Climate Models	Precipitation				Temperature			
		SIM (mm/day)	MRE (%)	COOR	NSE	SIM (℃)	MRE (℃)	COOR	NSE
1	BCC-CSM1.1	1.68	26.0	0.76	0.51	2.76	-3.77	0.98	0.84
2	CCSM4	2.30	72.3	0.87	-0.17	5.83	-0.70	0.99	0.96
3	CESM1-CAM5	2.54	89.7	0.89	-0.60	5.99	-0.54	0.98	0.97
4	CSIRO-MK3.6.0	1.68	25.7	0.89	0.62	4.06	-2.47	0.99	0.89
5	CNRM-CM5	1.74	30.1	0.86	0.65	3.82	-2.71	0.99	0.90
6	FGOALS-g2	2.04	52.8	0.86	0.33	3.67	-2.86	0.99	0.88
7	GFDL-CM3	2.34	74.7	0.81	-0.09	4.68	-1.85	0.99	0.94
8	HadCM3	1.95	45.6	0.80	0.33	5.41	-1.12	0.99	0.96
9	INM-CM4	2.38	77.9	0.86	-0.18	2.80	-3.73	0.98	0.81
10	IPSL-CM5A-LR	1.75	30.6	0.86	0.62	4.15	-2.38	0.98	0.91
11	MIROC-ESM	2.38	77.6	0.80	-0.58	6.54	0.01	0.98	0.97
12	MPI-ESM-LR	2.30	71.9	0.78	-0.15	7.36	0.84	0.98	0.97
13	MRI-CGCM	1.12	-16.0	0.80	0.59	3.57	-2.95	0.99	0.86
14	NorESM1-M	2.74	104.6	0.87	-1.20	2.78	-3.75	0.98	0.82

4. Water resources changing analysis in Yellow River Basin based on CLHMS

4.1. Future Scenario Experiment Data and Its Correction

To analyse the water cycle change trend in the coming years and discuss the influence of climate change on water cycle in Yellow River Basin, this section uses the CMIP Representative Concentration Pathways (RCPs) as the atmospheric drive of CLHMS, simulating the response of water cycle under different scenarios. According to China's medium-term and long-term development plants and the word developing level, we select low, mid and high typical standard RCP scenarios, which is RCP2.6, RCP4.5 and RCP8.5.

It can be indicated from the section 3 that the simulation capability of CNRM-CM5 and IPSL-CM5A-LR are superior to other models. While, the resolution of CNRM-CM5 (256×128) is higher than IPSL-CM5A-LR (96×96). CNRM-CM5 has participated high, middle and low RCP scenario experiments, which can provide the driven data for CLHMS (table 3). Besides, some study demonstrate that CNRM-CM5 have a good simulation capability in extreme event and subtropical anticyclone of West Pacific Ocean [18, 19].

CNRM-CM5 model is developed by CNRM-GAME and CERFACS. It contains atmospherical model ARPEGE-Climate v5.2, land surface model SURFEX/TRIP, ocean model NEMO v3.2, sea ice model GELATO v5 and OASIS v3 coupler [20] with 1.4°atmospherical model resolution, 31 layers in vertical direction and 1° ocean model resolution.

Compared with the meteorological data need by CLHMS model, CNRM-CM5 data only has the variable "surface down welling shortwave radiation" instead of 4 short-wave radiation type. Based on the difference of incident mode and wave length, short-wave radiation can be divided into near infrared beam downward solar flux, near infrared diffuse downward solar flux, visible beam downward solar flux and visible diffuse downward solar flux. It is commonly held that direct beam solar flux accounts for 70% of short-wave radiation, diffuse solar flux for 30%, and visible light and near infrared light are respectively for 50%. Therefore, this study distribute the downward short wave radiation of 35%, 35%, 15% and 15% respectively to visible beam downward solar flux, near IR beam downward solar flux, visible diffuse downward solar flux and near IR diffuse downward solar flux. The surface pressure needed by the model was calculated by surface temperature, height above sea level and sea level pressure value, to convert the sea level pressure data in CNRM-CM5.

Table 3. CLHMS required variables and corresponding variables in CNRM-CM5

No.	Variable in CLHMS	Unit	Variable description in CNRM-CM5
1	Precipitation	$Kg/m^2/s$	Precipitation
2	Air temperature 2m	K	Near-Surface Air Temperature
3	Eastward Wind	m/s	Eastward Near-Surface Wind
4	Northward Wind	m/s	Northward Near-Surface Wind
5	Specific Humidity	Kg/kg	Near-Surface Specific Humidity
6	Surface pressure	$Pa(N/m^2)$	Sea Level Pressure
7	Total Cloud	%	Total Cloud Fraction
8	Downward longwave radiation flux	W/m^2	Surface Downwelling Longwave Radiation
9	Near IR beam downward solar flux	W/m^2	Surface Downwelling Shortwave Radiation,
10	Near IR diffuse downward solar flux	W/m^2	
11	Visible beam downward solar flux	W/m^2	
12	Visible diffuse downward solar flux	W/m^2	

4.2. Experiment design and data correction

This section uses the climate estimation result of the 21st century of high-resolution climate model CNRM-CM5 under the low, middle and high greenhouse gas concentration trajectories (RCP2.6, RCP4.5 and RCP8.5), drives the Coupled Land-surface and Hydrological Model System (CLHMS), estimate the water cycle changes in YRB.

To reduce the systematic error in the GCM's simulation result, while the RCPs output from the GCM needs to be corrected for biases [21]. Therefore, a statistical bias correction is applied to daily precipitation and daily temperature with the observed EA precipitation data and CN05 temperature data. The correction formula is as follows:

$$T_{CR}(x,y,t) = T_{RCP}(x,y,t) + (T_{obs}(x,y,mon) - T_{GCM}(x,y,mon)) \quad (4)$$

$$P_{CR}(x,y,t) = P_{RCP}(x,y,t)\frac{P_{obs}(x,y,mon)}{P_{GCM}(x,y,mon)} \quad (5)$$

Among the formula, T_{RCP} and P_{RCP} represent the given value of temperature and precipitation to be corrected, T_{CR} and P_{CR} represent the corrected value. T_{obs} and P_{obs} are the observed multi-year average temperature and precipitation data during 1962 to 2005, while T_{GCM} and P_{GCM} are the historical run's simulation values of the multi-year average temperature and precipitation.

The experiment design is as follows: the bias corrected RCPs run's daily data (table 3) of CNRM-CM5 is used to force the CLHMS model to simulate the 95-year water cycle process from 2006 to 2010. The first 15 years is considered as the cold start period, only the simulation result from 2020 to 2100 is used for analysis. This section focuses on the change trend of the future climate and water cycle. The variation of total water resources in YRB is compared, in the meantime, the flood frequency of Huayuankou station (Figure 1) is also analysed in this section.

4.3. Water Cycle Changes

The IPCC AR5 RCPs are named according to their 2100 radiative forcing level. The RCP 2.6 pathway is representative for low greenhouse gas concentration scenario, its radiative forcing level first reaches a value around 3.1w/m^2 around 2050, then returning to 2.6 W/m^2 by the end of 21st century [22]. The RCP 4.5 is a stabilization scenario where total radiative forcing is stabilized at 4.5 W/m^2 before 2100 [23]. The RCP 8.5 is a high greenhouse gas concentration scenario, which characterized by increasing greenhouse gas emission [24].

In Yellow River Basin, the trend of average precipitation in the 21st century is shown in figure 3. The results show that the inter-annual rainfall varies greatly. A changing rate of 2.38mm/10a in precipitation is estimated for the scenario of RCP2.6. Under the RCP4.5 scenario, the changing rate of rainfall is 4.42mm/10a. For RCP 8.5, we observe a significant change in precipitation. The changing rate is about 17.4 mm/10a.

the CLHMS model simulation result shows that the average total water resources of YRB in 21st century in RCP2.6, RCP4.5 and RCP8.5 scenarios are respectively 52.2, 59.8 and 65.0 billion m^3, which respectively holds -30%, -24% and -17% deviations to the total water resource from 1962 to 2006. Figure 3 indicates the decadal changes of surface and groundwater resource quantity of YRB in 21st century under RCPs, figure 3 also shows the multi-year water resource quantity of 45-year reference period (1962-2006). All in all, Yellow River will maintain the water deficiency situation since 1980, except that the water resource quantity in 2090 simulated in RCP8.5 scenario is over the water resource quantity (78.76 billion m^3) in the reference period from 1962 to 2006.

Based on the observed monthly streamflow data from 1956 to 2000, the maximum average monthly runoff in Huayuankou station was 5952m^3/s (August, 1958). Defining the year that average monthly streamflow excesses 4000 m^3/s as a flood year, from 1956 to 1989 (34 years in total), there was 16 high flow years. But with the decrease of precipitation in the Yellow River Basin, the maximum average monthly runoff of Huayuankou station in 1990s is only 3639 m^3/s (August, 1993). This section defines the year that the single average runoff is over 4000 m^3/s as the flood year to analyse the level and frequency of the future flood in Yellow River of 21st century.

Under RCP2.6 scenario, there are 8 flood years during 2020 and 2100, among which, there is 1 year (the middle period of 21st century) that the maximum monthly runoff is over 5000 m^3/s; under RCP 4.5 scenario, there are 9 flood year while there is only 1 year that the maximum monthly runoff is over 5000 m^3/s, which also happens in the middle period of 21st century. Under RCP8.5 scenario, there are 17 year flood year in Yellow River Basin in the coming hundred years, while the last 15 years (2085-2100) will have 4 runoffs that excess 1958 maximum flood in 21st century.

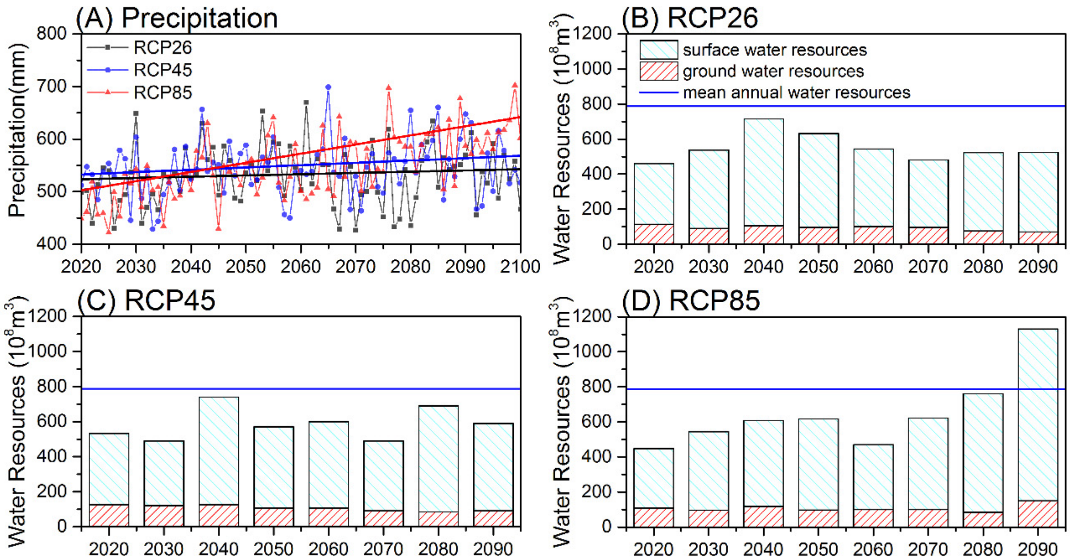

Fig. 3. The trend of precipitation (A) and water resources (B,C,D) in Yellow River Basin in the 21st century

5. Discussion and conclusions

The skill of 14 IPCC AR5 GCMs for simulating temporal and spatial temperature and precipitation in the Yellow River basin has been evaluated. The results show that most of the GCMs have a better ability to simulate the temperature than that of precipitation. Compared with the observed data, the model of CNRM-CM5 and IPSL-CM5A-LR shows an optimal simulation skills in the study area.

Based on the simulation capability evaluation, the RCPs scenarios (RCP2.6, RCP4.5 and RCP8.5) data set of optimal GCM was bias corrected and used to drive the Coupled Land surface and Hydrological Model System (CLHMS). The impacts of future climate changes on water resources and extreme flows in Yellow River Basin was examined.

The simulation result indicate that the water shortage of Yellow River Basin will continue while the extreme flood may appear in the future. The CLHMS model simulation result shows that the average total water resources of Yellow River Basin in 21st century in RCP2.6, RCP4.5 and RCP8.5 scenarios respectively holds -30%, -24% and -17% deviations to the total water resource from 1962 to 2006. RCP 8.5 scenario simulation shows a decrease of water resources in the early and mid 21th century, but after 2080, with the increase of rainfall, the extreme flood events tends to increase.

Acknowledgements

This research was jointly supported by the National Natural Science Foundation of China (Grant Nos. 51309246, 41575095)

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