A point-by-point response to the reviews for “Dominant climatic factors driving annual runoff changes at the catchments scale over across China” by Huang et al.

Manuscript Details:
Dominant climatic factors driving annual runoff changes at the catchments scale over across China (HESS-2015-493)

Authors:
Z. Huang, H. Yang and D. Yang

We thank three reviewers for their very valuable comments. Below are mentioned responses to them point-by-point.

Response to M. Renner

Referee comments in Italics

The authors apply the runoff elasticity method of Yang and Yang (2011) to mainland China and thereby extend work by Yang et al., (2014). The method is based on a Budyko framework and a first order derivative of the Penman equation to analyze the effect of observed trends in meteorological variables such as precipitation, net radiation, temperature, wind speed and relative humidity. This manuscript analyzed the same dataset as Yang et al., (2014) who also presented a runoff elasticity method but not with respect to forcing variables of the Penman equation.

Response:

We are very grateful for your positive evaluation and detailed comments. And we are revising this manuscript following your suggestions. I believe that it will lead to a great improvement in this manuscript.

1. Scientific interest

The reported trends between 1960-2010 in these variables are remarkable and deserve attention because they may have direct impacts on potential evaporation and the water balance. The proposed method by Yang and Yang (2011) is a quantitative and theory based way to estimate how runoff might have changed due to these trends. As the authors show in this manuscript these trends vary spatially in China and the sensitivity of the different catchments to change varies as well.

Unfortunately the authors do not discuss their results in depth. For example one potentially interesting point which is somewhat hidden in the results is that decreases both in net radiation and wind speed partly compensate the runoff decline caused by precipitation decreases. Also no discussion or further references on the origin, magnitude of the trends in the meteorological variables such as net radiation or wind speed is presented. Is the reduction in net radiation a result of decreasing solar radiation induced by atmospheric dimming or due to other variables? Such a discussion would help to understand the climatic impacts and their implications on water resources.

Response:

Thanks for your positive evaluation and detailed comments. We are revising the manuscript following your comments and suggestions.

2. Novelty

The manuscript largely builds on previous work. The method, its comparison to hydrological modeling studies and an application to a large set of 89 catchments was presented by Yang and Yang (2011). The same dataset and the elasticity of precipitation and potential evaporation was recently presented by Yang et al., (2014). Some maps shown in this manuscript are very similar to those presented in Yang et al., (2014). For example compare Fig. 7 with Fig. 9 of Yang et al., (2014). Because this *overlap is substantial (see also similarity report) I strongly recommend to discuss and explain the novelty and implications of this research.*

Response:

Thanks for your comments. We think that the contribution of this manuscript are: (1) separating the contribution to runoff from precipitation, temperature, wind speed, net radiation and relative humidity, while Yang et al. (2014) only separated that from precipitation and potential evaporation; and (2) detecting the dominant climatic factor driving annual runoff change, which shows a regional variation, i.e. precipitation in most of the 207 catchments, net radiation in the lower reach of Yangtze River Basin and the southeast, and wind speed in part of the northeast.

3. Comparison vs. validation

The authors only compare their method with hydrological modeling results. This comparison is useful but is not a validation with independent data. Validation of runoff elasticity is generally difficult when other changes on catchment properties, water extraction, have been happening at the same time. Within the presented test catchments the actual runoff change was always quite different to the estimated change by climate in on case even the sign was different (Table 3). In addition, while the data is presented on catchment level, apparently no runoff data was presented. I am wondering why is there no comparison with of the estimated runoff change with the actual runoff changes? This would give an indication on the importance of the climatic factors on actual runoff changes.

Response:

Thanks for your comments. As you said, climate change, catchment properties, and water extraction have great impacts on runoff when they happen at the same time, which makes it difficult for the validation. However, in this study, we only try to analyze the impacts of climate change on runoff and to detect the dominant climatic factor driving annual runoff change. In the further research, we will study on the effect from human activities. In this study, the reason why we compared their method with hydrological modeling results is that the observed runoff includes the effects not only from climate change but also from human activities, while the hydrological modeling runoff doesn't include human activities.

4. Definition of the aridity index/energy limit

Budyko defined the energy limit through the water equivalent of net radiation Rn. Because Rn is not measured densely enough Rn was replaced by some formulation of potential evaporation (UNEP 1992, World Atlas of desertification), which might be estimated by meteorological variables such as was done in this work. Interestingly, by using the approach of Yang and Yang (2011), net radiation reappears as control on evapotranspiration but in a different setting as originally proposed by Budyko's energy limits. Please discuss this aspect.

Response:

Thanks for your comments. Evapotranspiration depends on the energy supply and water supply. Budyko defined the energy limit through the water equivalent of net radiation *Rn*, at large spatial scale. However, at a small spatial scale, except net radiation, the energy imported by horizontal advection will affect water and energy balances. And the effect of the horizontal advection can be exposed by climatic variables, such humid, air temperature and etc. Therefore, we chose potential evaporation to represent energy supply. And we are adding more discussion on this aspect.

5. Format / presentation

The paper is written in rather focused way and is mostly easy to follow for the interested reader. However, the English needs to be improved throughout the manuscript. In particular the results section uses past tense when describing results. Some figures are too small to be able to read annotations and legends. The legends must also be harmonized among similar maps to allow a visual comparison.

Response:

Thanks for your comments. In the revised version, we will improve the English and the figures to make the manuscript better.

6. Further Comments:

6.1-Section 5.1 Discussion of climate sensitivity estimates:

a) I wonder why other estimates using the same method / data should be different, please clarify!

b) If the cited estimates from the literature are independently derived, I advise to make a table which is easier than having all these numbers in the text.

Response:

a) Thanks for your comments. Yang and Yang（2011）evaluated climate elasticity to runoff in 89 catchments of the Yellow River basin and the Hai River basin. Tang et al.(2013) evaluated climate elasticity to runoff in the whole Yellow River basin. The main cause is the scale of study region. For the Yellow River basin, Yang and Yang（2011）selected about 50 small catchments, and Tang et al.(2013) treated it as one basin. In our study, we divided it into 29 catchments.

b) Thanks for your comments. Following your suggestion, we will make a table to compare the results of our study with the cited estimates in the revised manuscript.

6.2 -Section 5.1 Discussion of temperature sensitivity:

The whole paragraph starting on page 12925L12 is not very clear and needs a better presentation. For example results on $\partial E_0 / \partial \Delta$ *and* $\partial E_0 / \partial e_s$ *are discussed but I could not find them in the results section.*

Response:
Thanks for your comments. We will make a better presentation of this part in the revised manuscript.

6.3 -The last paragraph of section 5.1 seems to be copied from Yang and Yang (2011)

Response:
Thanks for your comments. We will revise this part.

6.4 -Please, provide the reference for Eq.12?

Response:
Thanks for your comments. The reference for Eq.12 will be added in the revised version.

6.5 State that Eq.12 is an empirical formulation for net radiation

Response:
Thanks for your comments. “Eq. is an empirical formulation for net radiation” will be added in the revised vision.

6.6 P12917L3: missing word
Response:
Thanks for your comments. We are sorry for carelessness. It should be “80 second-level”.

6.7 P12919L21: Maidment
Response:
Thanks for your comments. We are sorry for the spell mistake. We amended it as “Maidment” in the revision.

6.8 P12920L5: change to “Comparison of the climate elasticity method with hydrological models”
Response:
Thanks for your comments. We have changed it following your suggestion.

6.9 P12920L11 remove and rephrase “provided strong evidence” see earlier comments
Response:
Thanks for your comments. We will make a appropriate presentation of this part in the revised manuscript.

6.10 P12920 / Figure 2b: What data has been used for figure 2B?

Response:
Figure 2B showed the relative error (%) caused by the first-order approximation, where dE01 and dE02 are the potential evaporation change (mm) calculated by Eq. (9) and that by Eq. (17), respectively. Figure 2B used the data of annual climatic factors in 207 catchments which were interpolated from the meteorological station observation. To a better understanding, we will add more description in the revision.

6.11 P12921L11: Does it mean that runoff on map in Figure 3f was estimated by a Budyko function, rather than actual data?
Response:
In P12917L1,the mean runoff was calculated according to mean annual precipitation and runoff ratio, and runoff ratio was estimated by Hydrological Bureau according to observed precipitation and runoff. Unfortunately, we can't collect the first-hand runoff data for all the 207 catchments.

6.12 P12921L21: rephrase sentence, avoid "caused" because this is just an estimate.
Response:
Thanks for your comments. We replaced it with "result in" in the revised version.

6.13 P12921L25: why is temperature sensitivity reported in / ℃ and not as percentage %? In the moment one cannot compare the sensitivities and related attributed changes in runoff. This is related to Eq. 9. Please clarify and adapt.
Response:
Thanks for your comments. In Eq.(10), the temperature change was reported in ℃, which is different from other climate factors. This is because people are generally used to concern on the runoff change caused by 1 ℃. In addition, some catchments possibly have a mean annual air temperature below zero, which will lead to a change in sign. Hence, in this study, temperature sensitivity reported in ℃ may easy to understand.

6.14 P12927L13: What is meant by "small hydrology changes"?
Response:
Thanks for your comments. We wanted to express a little change in runoff and precipitation. We will give a better representation in revised version.

6.15 P12928L8: unclear, please rephrase
Response:
Thanks for your comments. Changing original text "the error of ε_P caused by first-order approximation can be discounted, but the error will increase with changes increasing with a 0.5−5% relative error in ε_P When ΔP = 10 mm and a 5−50% relative error in ε_P When ΔP = 100 mm." into "the error of ε_P caused by

first-order approximation can be neglected, but the error will increase with precipitation changes increasing, with a 0.5−5% relative error in ε_P when ΔP = 10 mm and a 5−50% relative error in ε_P when ΔP = 100 mm.”

6.16 Table 1: Variable z from logarithmic wind profile is not reported.
Response:
We will add more description. The wind speed at a height of 2 m was estimated from a logarithmic wind profile based on the observed wind speed at the height of 10 m.

6.17 Table 3: a) column headers mistake b) report units c) Which period is considered form the changes d) Consistent with P and PET report absolute values of R
Response:
Thanks for your comments. We have revised them in the revision as follow:

a) Changing the first “Upper Hanjiang River Basin” into “Upper Luan River Basin”;
b) Adding the units in the revision;
c) Adding explanation on the period (the change was regressed according the annual value from 1961-2010);
d) Adding R into the Table.

6.18 Figure 1b) only two test catchments are shown. Consider to highlight these test catchments in Fig 1a).
Response:
Thanks for your comments. We will redraw this figure following your suggestion.

6.19 Figure 3: caption delete first wind speed
Response:
Thanks for your careful review. I am sorry for our carelessness. We deleted the first wind speed in the revision.

6.20 Figure 4: Do elasticities add up to 1?
Response:
In theory, it should be 1.

6.21 Figure 5: Much too small to read! Increase size of plots. Maybe combine 1 and 2 panels by only showing significant catchments or using bold borders. The unit for the temperature trend seems wrong.
Response:
Thanks for your suggestion. We redraw it and corrected the unit of the temperature trend in the revision

6.22 Figure 6: Use the same color legend for all panels!
Response:

Thanks for your comments. We will use the same color legend for all panels in the revision.

6.23 Figure 7: Almost the same as in Yang et al., (2014)!
Response:
Thanks for your comments. Figure 7 will be deleted and a reference will be added.

Response to M. Ashok

Referee comments in Italics

Overall it is a very good article and it can be publishable after considering the following comments: If the authors do not agree to the comments, a justification can be helpful.

Response:

We are very grateful for your positive evaluation and detailed comments. And we are revising this manuscript following your suggestions. I believe that it will lead to a great improvement in this manuscript.

1. Data source: While evaluating the impacts of climate on runoff, we should always use the catchments which are minimally impacted by human disturbances by the ways of dams, reservoirs or irrigation. Else, that would result in improper assessment of influence of climate on annual runoff. Similarly, most of the studies related to climate elasticity and Budyko hypothesis have explored regions which have minimal impact of anthropogenic activities. Is that factor taken into account? If so, please mention that in the text otherwise it can be highlighted as future study.

Response:

Thanks for your comments. As you pointed out, runoff has been impacted by human activities in most catchments of China. In this manuscript, therefore, our objectives include: (1) to evaluate the contribution of climate change on runoff based on the Budyko hypothesis; (2) to detect the dominant climatic factor and understand its regional characteristics. Consequently, we used the Budyko hypothesis through considering the parameter n as constant for each catchment in order to evaluate the impacts from climate change, and divided the whole China, into 207 third-level catchments to understand the regional characteristics of the impact from climate change. Following your suggestions, we will add more and explanation and discussions in the revision and on revise this manuscript and improve this method to study the impact from human activities in the future study.

2. Purpose of Validation of the climate elasticity method: The authors have compared hydrologic model results with climate elasticity results. Based on table 3, one can observe that, (△R/△Re) is comparatively closer to the observed data (△R/△Ro) in only upper Hanjiang river basin. The authors have evaluated all the catchments in china based on this single river basin. To prove that the climate elasticity method is superior to hydrologic modeling on this evidence is not statistically significant. Usually, Hydrologic models are more prone to parameter uncertainties and are difficult to calibrate. But, once properly calibrated, they act as proxies for evaluating runoff where data is unavailable. Whereas, the climate elasticity models based on Budyko are easier to compute but cannot be applied to regions were the data is scarce.

Each method has its pros and cons. Therefore, the authors can provide a justification on the choice of climate elasticity model in a more informed way.

Response:

Thanks for your comments. The main purpose of this study was separating the effects of different climatic factors on runoff and detecting the dominant climatic factor driving annual runoff change at catchment scale in China. The climate elasticity method outlined by Yang and Yang (2011) aimed to assess and separate the effects of different climatic factors on runoff. To validate the climate elasticity method, we must evaluate the impacts of climate change to runoff and then compare it with observed runoff change caused by climate change. However, both anthropogenic activities and climate change have become important factors driving runoff change, and observed runoff data include the effects not only from anthropogenic activities but also from climate change. Therefore, we collected the modeling runoff change and the contribution from climate change for the three catchments from literatures, to validate the climate elasticity method. We agree with your comments that there are large uncertainties in parameters of the hydrological models. Those modeling results, simulated by hydrological models through keeping parameters constant, were assumed as the impact of climate change. And this assumption has been making in previous researches. So we compared hydrologic model results with climate elasticity results. Following your suggestions, we will compare the two methods in the revision.

3. Comments: This article applies the runoff elasticity method as outlined by Yang and Yang (2011) and applies it to the dataset utilized in Yang et al., (2014). Hence, this can be termed as an extension of both these works. It provides the runoff elasticity to net radiation, temperature, wind speed and relative humidity which was not earlier evaluated. Even though this article is novel in this direction, there appears to be very less depth in their discussions and results. For example, in figure 8, what can be a possible reason which explains the dominance of radiation and wind speed in the south eastern and north eastern regions?

Response:

Thanks for your comments. It is a very valuable suggestion for us, and points out the direction in the revision. We will make a deeper discussion in the revision.

Response to Anonymous Referee #3

Referee comments in Italics

This study investigated the dominant climatic factors driving annual runoff change in basins of mainland China. The story is interesting and the overall organization is clear. Three main concerns need to be addressed though before the paper reaches publishable standard.

Response:

We are very grateful for your positive evaluation and detailed comments. And we are revising this manuscript following your suggestions. I believe that it will lead to a great improvement in this manuscript.

1. The authors used the climate elasticity method to identify the influence of climate factors on runoff at basin level. The climate elasticity method essentially is a statistical method, which gives results based on data analysis. The method itself is not novel and I didn't see any revision or improvement. So the scientific contribution of this paper is little from the methodological perspective.

Response:

Thanks for your comments. The climate elasticity was general estimated according to a statistical method based on data analysis. Differently, in this manuscript, we estimated the climate elasticity according to the differential of the Budyko hypothesis (Yang and Yang, 2011), which has a physical basis and only requires the mean annual precipitation and potential evaporation. Though no improvements in methodology, we think that the contributions of this manuscript are: (1) to separate the contribution to runoff from precipitation, temperature, wind speed, net radiation and relative humidity; and (2) to detect the dominant climatic factor driving annual runoff change, which shows a dramatic regional variation, i.e. precipitation in most of the 207 catchments, net radiation in the lower reach of Yangtze River Basin and the southeast, and wind speed in part of the northeast.

2. Elasticity maps showing the impacts of climate parameters on runoff were presented but not analyzed in depth. For example, why net radiation is the dominant player in the lower reach of Yangtze River Basin and why wind speed is important in part of the northeast China? Implications and reasons behind the maps would be much more meaningful than simply showing the map.

Response:

Thanks for your comments. It is a very valuable suggestion for us, and points out the direction in the revision. We will make a deeper discussion in the revision.

3. Grammar and spelling errors affect reading experience. The authors should do a thorough check to improve the writing. Therefore, I would suggest a major revision based on the concerns.

Response:

Thanks for your comments. In the revised version, we will improve the English and the figures to make the manuscript better.

Specific comments:

Page 12912, 2nd paragraph: the authors didn't explain why chose the climate elasticity method over others.

Response:

Thanks for your comments. This method has the advantage of requiring only mean and trend of climate and basin variables, and not requiring extensive historical measurements. And we will explain it in the revision.

Page 12915, line 2: "abvious" should be obvious

Response:

Thanks for your comments. We are sorry for the spell mistake. We amended it as "obvious" in the revision.

Page 12917, line 12-17: it is not clear how the authors processed the data. Is the first step interpolating station data to grid level? How was that performed?

Response:

Thanks for your comments. Yes, the first step was interpolating station data to grid level. Firstly a 10 km grid which covers the study area was prepared and then we interpolated observations data of the meteorological stations to grid. The interpolation method for climatic factors was an inverse-distance weighted technique, except air temperature which must consider the influence of elevation. In the revision, we will add more explanations

A list of all relevant changes made in the manuscript for “Dominant climatic factors driving annual runoff changes at the catchments scale over across China” by Huang et al.

Manuscript Details:

Dominant climatic factors driving annual runoff changes at the catchments scale over across China (HESS-2015-493)

Authors:

Z. Huang, H. Yang and D. Yang

We thank three reviewers and editor for their very valuable comments. Below is a list of all relevant changes made in the manuscript.

Relevant changes made in the manuscript are as follows:

1) A co-author was added due to his great contribution to the manuscript revision.

2) More details about the definition of the aridity index/energy limit were added in the manuscript.

3) A catchment in humid region with observed data was added for validation of the climate elasticity method.

4) The air temperature elasticity, the contribution of air temperature to runoff change and the dominant climatic factor driving annual runoff change were revised;

5) Changes in climate factors, which were reported by Yang et al.(2015), were deleted in the revised manuscript.

6) In part 5.1, two tables were made to compare the evaluated climate elasticity and the estimates from the literature, which is easier for observation.

7) Better presentation of the air temperature elasticity in part 5.1.

8) More discussion about the contribution of climatic factors to runoff change in part 5.2.

9) Necessary revision for Tables and Figures.

The following pages are a marked-up manuscript version. Revisions in the text are shown using yellow highlight for additions, and strikethrough font for deletions. We hope that the revisions in the manuscript and our accompanying responses will be sufficient to make our manuscript suitable for publication in HESS.

A marked-up manuscript 1 version:

Dominant climatic factors driving annual runoff changes at the catchment~~s~~ scale ~~over~~ across China

Zhongwei Huang[1, 2,3] , ~~and~~ Hanbo Yang[1]* and Dawen Yang[1]

[1]{State Key Laboratory of Hydro-Science and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing, 100084, China}

[2]{Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China}

[3]{University of Chinese Academy of Sciences, Beijing 100049, China}

Correspondence to: Hanbo Yang (yanghanbo@tsinghua.edu.cn)

Abstract

With global climate changes intensifying, the hydrological response to climate changes has attracted more attention~~s~~. It is beneficial not only for hydrology and ecology but also for water resource~~s~~ planning and management to ~~reveal~~understand the impact~~s~~ of climate change on runoff. ~~It's of great significance of climate elasticity of runoff to estimate the impacts of climatic factors on runoff.~~ In addition, there are large spatial variations in climate type and geographic~~y~~ characteristics across~~over~~ China. To ~~get~~ gain a better understanding of the spatial variation of the response of runoff ~~response~~ to changes in ~~climate~~ climatic factors~~variables change~~ and to detect the dominant climatic factors driving changes in annual runoff~~ change~~, we chose the climate elasticity method proposed by Yang and Yang (2011), where the impact of the catchment characteristics on runoff was represented by a parameter *n*. The results showed that the dominant climatic factor driving annual runoff ~~is~~ was precipitation in ~~the~~ most parts of China~~,~~; net radiation in some catchments of the lower reaches of the Yangtze River basin, the Pearl River basin, the Huai River basin and the ~~Southeast~~ southeast

~~Area~~area~~,~~; air temperature in the upper reaches of the Yellow River basin and the north part of the Songhua River basin; and wind speed in part of the northeast, part of Inner Mongolia.

~~and wind speed in part of the Northeast China.~~

1 Introduction

Climate change has become increasingly significant, and it has important impacts on the hydrologicaly~~y~~ cycle and~~ the~~ water resource management. Changes in climatic factors and runoff have been observed in many different regions of China. ~~The r~~Reductions ~~of ~~in precipitation occurred in the Hai River basin, the upper reaches of the Yangtze River basin and the Yellow River basin, and ~~the ~~an increase occurred in ~~the in the ~~western China (Yang et al., 2014). A 29% decline ~~of ~~in surface wind speed occurred in China during 1966 to 2011~~, which would have lead to a 1 – 6% increase in runoff and a 1 – 3% decrease in evapotranspiration at most regions in China~~ (Liu et al., 2014). Most of the river basins in n~~North ~~orth China have exhibited an obvious decline in mean annual runoff, such as the Shiyang River basin (Ma et al., 2008), the Yellow River basin (Yang et al., 2004;Tang et al., 2007;Cong et al., 2009), and the Hai River basin (Ma et al., 2010). The hydrologic processes have been influenced by different climatic factors. For example, a decline in land surface wind speed ~~could ~~can lead to a decrease in evapotranspiration, and changes in precipitation may affect water generation and concentration. However, the dominant climatic factor driving annual runoff change is still unknown in many catchments ~~of~~in China.

There are several approaches to investigate the ~~feedback ~~impacts of annual runoff onto climate change, ~~such as~~including~~ the~~ hydrologic models (Yang et al., 1998;Arnold et al., 1998;Yang et al., 2000;Arnold and Fohrer, 2005), the climate elasticity method (Schaake, 1990;Sankarasubramanian et al., 2001) and the statistics method (Vogel et al., 1999). T~~herein,~~ ~~t~~he climate elasticity method, which has the advantage of requiring only the mean and trend of climate and basin variables and not requiring extensive historical measurements, ~~–~~was widely used in quantifying the effects of climatic factors on runoff, such as in the Yellow River basin (Zheng et al., 2009;Yang and Yang, 2011), the Luan River basin (Xu et al., 2013), the Chao–Bai Rivers basin (Ma et al., 2010), and the Hai River basin (Ma et al., 2008; Yang and Yang, 2011).

A simple climate elasticity method was first~~ly~~ defined by Schaake (1990) to estimate the impacts of precipitation (P) on annual runoff (R):

$$\frac{dR}{R}=\varepsilon_P(P,R)\frac{dP}{P}, \tag{1}$$

where ε_P is the precipitation elasticity. To consider the effects of precipitation and air temperature on runoff, Fu et al. (2007) calculated the runoff change as:

$$\frac{dR}{R}=\varepsilon_a\frac{dP}{P}+\varepsilon_b\frac{dT}{T}, \tag{2}$$

where ε_a and ε_b are the precipitation elasticity and air temperature elasticity, respectively.

Five categories of methods can be used to estimate climate elasticity ~~(Sankarasubramanian et al., 2001),~~ (Sankarasubramanian et al., 2001). ~~and t~~The analytical derivation method has been widely used in many studies because it is ~~not only~~ clear in theory ~~but also~~ and does~~ not~~ not need a large amount of historical observed data. Arora (2002) ~~projected~~ proposed an equation to calculate~~d~~ the response of runoff to precipitation and potential evaporation~~ change~~:

$$\frac{\Delta R}{R}=[1+\frac{\phi F_0^{'}(\phi)}{1-F_0(\phi)}]\frac{\Delta P}{P}-\frac{\phi F_0^{'}(\phi)}{1-F_0(\phi)}\frac{\Delta E}{E}, \tag{3}$$

where $\phi=E/P$ and $F_0(\phi)$ is a Budyko formula and $F_0^{'}(\phi)$ is the derivation of~~to~~ ϕ. The climate elasticity of runoff was evaluated in the upper reaches of the Yellow River basin by using Eq. (3) (Zheng et al., 2009). To evaluate the impacts from other climatic factors, Yang and Yang (2011) proposed an analytical method, ~~which was~~ based on the Penman equation and the annual water balance equation, to ~~quality~~ quantify the runoff change relative to changes in different climatic factors. By taking advantage of the mean annual climatic factors in the study period, the runoff elasticity to precipitation (P), mean air temperature (T), net radiation (Rn), relative humidity (RH), and wind speed (U_2) were derived~~,~~. ~~and t~~The runoff change can be expressed as follows:

$$\frac{dR}{R}=\varepsilon_P\frac{dP}{P}+\varepsilon_{Rn}\frac{dR_n}{R_n}+\varepsilon_T dT+\varepsilon_{U_2}\frac{dU_2}{U_2}+\varepsilon_{RH}\frac{dRH}{RH}, \tag{4}$$

where ε_P, ε_{Rn}, ε_T, ε_{U_2}, and ε_{RH} are the runoff elasticity relative to precipitation (P), net radiation (Rn), mean air temperature(T), wind speed (U_2), and relative humidity (RH), respectively. However, this method was only tested in several catchments of ~~the~~ non-humid ~~Northern~~ north China.

There are large spatial variations in both ~~geography~~ geographic characteristics and climate types ~~over~~ across China, ~~which would~~ resulting in a large variation in the hydrologic response to climate change. Therefore, the current study aims to~~:~~ (1) further ~~validating~~ validate the method proposed by Yang and Yang (2011), (2) ~~evaluating~~ evaluate the climate elasticity of climatic factors to runoff at the catchment~~s~~ scale ~~over~~ across China, and (3) ~~estimating~~ estimate the ~~impact of climate variation~~contribution of climatic factors ~~on~~ to runoff change and then detect~~ing~~ the dominant climatic factor driving annual runoff change.

2 Climate elasticity method based on the Budyko hypothesis

At the catchment scale, there is a relationship of evaporation with available water and available energy, referred as the Budyko hypothesis (Budyko, 1961). Budyko defined the available energy as the water equivalent of net radiation R_n at a large spatial scale. However, at a small spatial scale, except for net radiation, the energy imported by horizontal advection will affect water and energy balances. The effects of the horizontal advection can be exposed by climatic factors, such as humidity and air temperature. At the same time, this effect of net radiation and these climatic factors can be estimated by potential evaporation. Therefore, Yang et al. (2008) chose potential evaporation to represent available energy and further derived an analytical equation of the Budyko hypothesis as follows:

~~At catchment scale, there is abvious relationship between evaporation, precipitation and potential evaporation, which is referred as the Budyko hypothesis (Budyko, 1961). An analytical equation of the Budyko hypothesis was inferred by Yang et al. (2008):~~

$$E = \frac{E_0 P}{(P^n + E_0{}^n)^{1/n}} , \qquad (5)$$

where the parameter n represents the characteristics of the catchment, ~~for example~~ such as land use and coverage change, vegetation, slope~~s~~ and climate seasonality (Yang et al. 2014).

The water balance equation can be simplified as $P = E + R$ at the catchment scale for ~~the~~ a long term, so runoff can be expressed as follows:

$$R = P - \frac{E_0 P}{(E_0^n + P^n)^{1/n}}. \tag{6}$$

To attribute the contribution of changes in P and E_0 to runoff, Yang and Yang (2011) derived a new equation:

$$\frac{dR}{R} = \varepsilon_1 \frac{dP}{P} + \varepsilon_2 \frac{dE_0}{E_0}, \tag{7}$$

where ε_1 and ε_2 are the climate elasticity of runoff relative to P and E_0, respectively; and they can be estimated as $\varepsilon_1 = \frac{(1-\partial E/\partial P)P}{P-E}$ and $\varepsilon_2 = -\frac{\partial E/\partial E_0\, E_0}{P-E}$. The potential evaporation E_0 (mm day^{-1}) can be evaluatedby the Penman equation (Penman, 1948):

$$E_0 = \frac{\Delta}{\Delta+\gamma}(R_n - G)/\lambda + \frac{\gamma}{\Delta+\gamma}6.43(1+0.536U_2)(1-RH)e_s/\lambda, \tag{8}$$

and the physical meaning of these symbols ~~were~~ are shown in Table 1.

Similar to Eq. (7), the response of potential evaporation to climatic factors can be estimated as:

$$\frac{dE_0}{E_0} = \varepsilon_3 \frac{dR_n}{R_n} + \varepsilon_4 dT + \varepsilon_5 \frac{dU_2}{U_2} + \varepsilon_6 \frac{dRH}{RH}, \tag{9}$$

where $\varepsilon_3, \varepsilon_4, \varepsilon_5, \varepsilon_6$ are the elasticity of potential evaporation ~~to~~ relative to net radiation, air temperature, wind speed, and relative humidity, respectively. Therein, $\varepsilon_3 = \frac{R_n}{E_0}\frac{\partial E_0}{\partial R_n}$, $\varepsilon_4 = \frac{1}{E_0}\frac{\partial E_0}{\partial T}$, $\varepsilon_5 = \frac{U_2}{E_0}\frac{\partial E_0}{\partial U_2}$, and $\varepsilon_6 = \frac{RH}{E_0}\frac{\partial E_0}{\partial RH}$. Due to the complex relationship between E_0 and T, the value of $\frac{\partial E_0}{\partial T}$ was calculated by the finite difference method, while $\frac{\partial E}{\partial P}$, $\frac{\partial E}{\partial E_0}$, $\frac{\partial E_0}{\partial R_n}$, $\frac{\partial E_0}{\partial U_2}$ and $\frac{\partial E_0}{\partial RH}$ were calculated by the finite differential method.

Yang and Yang (2011) s~~S~~ubstitute~~ution~~ed ~~of~~ Eq. (9) into Eq. (7)~~ leads to~~and yielding the following:

$$\frac{dR}{R} = \varepsilon_1 \frac{dP}{P} + \varepsilon_2 \varepsilon_3 \frac{dR_n}{R_n} + \varepsilon_2 \varepsilon_4 dT + \varepsilon_2 \varepsilon_5 \frac{dU_2}{U_2} + \varepsilon_2 \varepsilon_6 \frac{dRH}{RH}. \tag{10}$$

Denoted Eq. (10) as follows:

$$R^* = P^* + R_n^* + T^* + U_2^* + RH^*, \tag{11}$$

where P^*, R_n^*, T^*, U_2^* , and RH^* symbolize the runoff changes caused by ~~-~~the ~~changing~~ changes in P, R_n, T, U_2 , and RH , respectively. The largest one among them is considered as the dominant climatic factor driving annual runoff change.

3 Data and method

3.1 Study region and data

The ~~Catchment~~ catchment information data set was collected from the Ministry of Water Resources of the People's Republic of China (Water Resources and Hydropower Planning and Design General Institute, 2011). In the data set, the catchment boundary and runoff ratio were available. Chinese water resources zoning was divided by level as follows~~ by level, and~~: there are 10 first-level basins, 80 second-level river basins and 210 third-level river basins (~~Shown~~ shown in Fig.1 (A)). T~~herein, t~~here are no observed meteorological data ~~in~~ on Taiwan Island and no runoff in two inland catchments in Xinjiang ~~province~~Province. Hence, 207 third-level catchments were selected in this study.

The m~~M~~eteorological data, obtained from 736 weather stations ~~during~~ between ~~the period~~ 1961and ~~-~~2010 from the China Meteorological Administration (CMA), included precipitation, surface mean air temperature, maximum air temperature, minimum air temperature, relative humidity, sunshine hours, and wind speed. In addition, daily solar radiation during the period 1961–~~—~~2010 was collected from 118 weather stations.

To ~~get~~ obtain the annual climatic factors in each catchment, first, a 10 km grid covering the study area was prepared. Second, we interpolated the observed data of the meteorological stations into a grid. The interpolation method used for climatic factors was an inverse-distance weighted technique, except air temperature, which must consider the influence of elevation (Yang et al., 2006). ~~firstly, a 10 km grid data set, which covers the study area, was prepared for interpolation from the observed meteorological data. Secondly~~Third, according to the 10 km grid data set, the average values of cliamt~~e~~ice factors of each catchment were calculated. ~~The interpolation method for climatic factors were an inverse-distance weighted technique, e~~

~~xcept air temperature which must consider the influence of elevation (Yang et al., 2006).~~

~~Since~~ Because only 118 weather stations directly measured solar radiation, the daily net radiation Rn (MJ m^{-2} day^{-1}) was calculated by an empirical formulation (Allen et al., 1998)~~as~~:

$$R_n = (1-\alpha_s)R_s - \sigma[\frac{(T_{\max}+273.15)^4 + (T_{\min}+273.15)^4}{2}] \quad (0.1+0.9\frac{n}{N})\times(0.34-0.14\sqrt{\frac{RH}{100}e_s} \qquad (12)$$

~~and t~~The physical meaning of these symbols ~~were~~ are shown in Table 2. Rs was calculated by using the Angström formulation (Angström, 1924):

$$R_s = (a_s + b_s \times \frac{n}{N})R_a, \qquad (13)$$

where R_a is ~~the~~ extra-terrestrial radiation; and a_s and b_s are parameters ~~which~~ that were calibrated using the data at the 118 stations with solar radiation observations ~~,~~ (Yang et al., 2006). In Eq. (12), e_s is estimated as:

$$e_s = 0.3054[\exp(\frac{17.27T_{\max}}{T_{\max}+237.3}) + \exp(\frac{17.27T_{\min}}{T_{\min}+237.3})]. \qquad (14)$$

The wind speed at the height of 2 m (U_2, m s^{-1}) was estimated from a logarithmic wind profile based on the observed wind speed at the height of 10 m~~Wind speed at a height of 2m (U_2, m s^{-1}) can be calculated by the observed wind speed at 10m height~~ (Allen et al., 1998):

$$U_2 = U_z \frac{4.87}{\ln(67.8z - 5.42)} = 0.75U_{10}. \qquad (15)$$

Based on Eq. (6), the runoff ratio (α) can be estimated as follows:

$$\alpha = \frac{R}{P} = 1 - \frac{E_0}{(E_0^{\ n} + P^n)^{1/n}}. \qquad (16)$$

Furthermore, the catchment characteristics parameter n was calculated according to α, E_0 and P.

3.2 Validation of the climate elasticity method

Two steps were taken for the validation of the climate elasticity method, namely validating Eq. (7) and validating Eq. (9).

~~To validate Eq. (7),~~ A catchment in a humid region with observed data for annual precipitation, annual potential evaporation and annual runoff from 1956 to 2000 was chosen to validate Eq. (7), namely the Upper Bijiang River basin (shown in Fig. 1(B)). The Upper Bijiang River basin is located in the upper reaches of the Lancang River basin, with 495mm mean annual precipitation and 243mm mean annual runoff. The results given by Eq. (7) were compared with the observed results. This approach is reasonable because this catchment is located in the southwest mountainous region, where there is no remarkable impact from human activities. However, in most regions, both anthropogenic activities and climate change have become important factors driving runoff change, and observed runoff data include the effects not only from anthropogenic activities but also from climate change. Therefore, we additionally collected the modeled runoff change and the contribution from climate change for another two catchments from the literature, to validate the climate elasticity method, ~~two catchments were chosen,~~ namely the Luan River basin and the ~~upper~~ Upper Hanjiang River basin (shown in Fig.1 (B)). The Luan River basin, located in North China, is a part of the Hai ~~river~~ River basin. It has a mean annual precipitation of 455 mm, 75–85% of which ~~concentrates~~ falls from June to September. The Upper Hanjiang River basin, lying in the middle and lower reach~~es~~es of the Yangtze River basin, ~~which is the largest tributary of the Yangtze River,~~ finally flows into the Danjiangkou R~~r~~eservoir ~~and has a length of about 925 km and an elevation of 3500–88 m~~. In the two catchments, runoff ~~has~~ undergoes a remarkable change, and the causes for this runoff change were analyzed ~~by~~ using hydrological models. Xu et al. (2013) assessed the response of annual runoff to anthropogenic activities and climate change in the Luan River basin by using the geomorphology-based hydrological model (GBHM)~~GBHM model~~. Sun et al. (2014) explored the contributions from climate change and variation of catchment properties variation to runoff change in the Upper Hanjiang River basin~~Danjiangkou basin~~ ~~by~~ using three different methods: ~~including~~ climate elasticity, ~~and~~ decomposition ~~methods~~, and ~~the~~ dynamic hydrological modeling methods. To validate the climate elasticity method, the results given by Eq. (7) were compared with the results in references Xu et al. (2013) and Sun et al. (2014).

Equation (9) is the first-order Taylor ~~expansion~~ approximation of the Penman equation. ~~On one hand, we~~ We first~~ly~~ evaluated the climate elasticity of potential evaporation relative to air temperature, net radiation, relative humidity, wind speed and the change in these climatic factors, ~~,~~and we further estimated the change in potential evaporation according to Eq. (9), denoted as E_0^*. On the other hand, we calculated the potential evaporation change (E_0^{**}) as:

$$E_0^{**} = \frac{f\left(T+dT, R_n+dR_n, U_2+dU_2, RH+dRH\right) - f(T, R_n, U_2, RH)}{E_0}, \tag{17}$$

where the function $f()$ represents the Penman equation. Then, the first approximation E_0^* was compared with E_0^{**}, and the relative error was defined as follows: $RE = (E_0^* - E_0^{**}) / E_0^{**}$, which was an effective criterion to assess Eq.(9). In addition, the data of annual climatic factors in 207 catchments, which were interpolated from the meteorological station observations were used for validation.

~~to evaluation the error of Eq. (9).~~

~~3.3 Trend analysis~~

~~The Mann–Kendall (MK) nonparametric test (Kendall, 1948;Kendall, 1990) is an effective statistical tool for trend detection, especially for hydrological and meteorological time series (Mainment, 1993). The MK nonparametric test is widely used for its convenient calculation processes. The sample data are not necessary to obey some specific distribution, but they must be serially indenpendent. In this study, we firstly evaluated the significance levels of the trend of the hydrological and meteorological time series which were set at 0.05 and 0.1, and then estimated the slope of the trend:~~

$$\cancel{\beta = median\left[\frac{(x_j - x_i)}{(j-i)}\right], \qquad (18)}$$

~~for all $i < j$; where β is the magnitude of trend, and $\beta > 0$ indicates an increasing trend, and β <0 indicates a decreasing trend.~~

4 Results

4.1 Validation of the climate elasticity method

Table 3 ~~showed~~ shows the comparisons of ~~climate contribution to~~ runoff change, which were ~~estimated~~ assessed by the climate elasticity method~~ and~~, the hydrological models and the observed data. The runoff changes were 6.9% and 8.4% in the Upper Bijiang River basin, −21.4% and −30.8% in the Upper Luan River basin, 9.1% and −31.4% in the Lower Luan River basin, and −19.0% and −27.6% in the Upper Hanjiang River basin, as evaluated by the climate elasticity method and the observed data, respectively.~~,~~ The results evaluated by the climate elasticity method performed well in comparison with the observed data in these basins except for the Lower Luan River basin where anthropogenic heterogeneity, such as irrigation and reservoir operation, may be an important factor driving runoff change. Conversely, t~~T~~he climate contribution to runoff was~~is~~ −14% and −21.4% in the ~~upper~~ Upper Luan River basin, 12.4% and 9.1% in the L~~l~~ower Luan River basin and −19.6% and −19.0% in the Upper Hanjiang River basin, ~~which were~~as estimated by the climate elasticity method and the hydrological models, respectively. These results were as expected and may provide an effective assessment of runoff change without consideration of anthropogenic heterogeneity, making it possible ~~provided a strong evidence for using~~to use the climate elasticity method to evaluate~~ the~~ climate elasticity and the response of runoff to climate change both in humid and arid catchments.

Figure 2 (A) ~~showed~~ shows the relationship between the potential evaporation change evaluated by Eq. (9) and that evaluated by Eq. (17), ~~and~~ with most of the points falling ~~were~~ around the line $y=x$. The relative error~~s~~ (RE) (shown in Fig.2 (B)) mostly ranged from −3~~–~~ to 1%. A ~~High~~ high ~~correlativity~~ correlation ~~of them~~ and ~~the~~ small relative errors show~~ed~~ the accuracy of Eq. (9), ~~which maked~~making it possible to express potential evaporation change as a function of the variation of cliamtic factors~~ variation~~.

4.2 The mean annual climatic factors

The mean annual precipitation, net radiation, air temperature, wind speed, and relative humidity for each catchment ~~during~~ between 1961 and ~~–~~2010 ~~were~~ are shown in Fig.3. The mean annual precipitation in China, which had a typical spatial variation that decreased from the southeast to the northwest, ranged from 30 mm~~/a~~ in the northwest inland to 1883 mm~~/a~~ in the southeast coastal area. ~~a, and it had a typical spatial variation of decreasing from the southeast to the northwest.~~

The net radiation differed from 3 to ~~–~~10 (MJ m^{-2} d^{-1}) in China, of which the largest value occurred in the Qinghai-Tibet Plateau and the lowest value occurred in the Sichuan Basin. The mean annual air temperature in China had a range of −3.3–23.8℃, with a typical spatial variation of decreasing from the south to the north. The wind speed ~~in~~ at a 2 m height in China ranged from 1 m/s to 4 m/s, ~~and~~ with the highest value occurring~~red~~ in the north and the coastland and the lowest value occurringe~~d~~ in the Sichuan Basin. The relative humidity, which ranged from 35% in the northwest to 82% in the southeast, had a positive correlation with the precipitation. According to Eq. (6), we can evaluate the mean annual runoff (shown in Fig. 3(F)). The annual mean runoff had a range of 0 mm~~/a~~ to 1176 mm~~/a~~, exhibiting ~~which had~~ a similar spatial variation with that of ~~pricipitation~~precipitation.

4.3 Climate elasticity of the 207 catchments

Figure 4 ~~showed~~ shows the climate elasticity of runoff to the climatic factors for each catchment. In the 207 catchments~~,~~, ~~precipitation~~ precipitation elasticity ε_P ranged from 1.1 to 4.75 (2.0 on average), indicating that a 1% change in precipitation leads to a 1.1–~~–~~4.75% change in runoff. The lowest value of ε_P, ~~ranged~~ ranging from 1.1 to 1.5, occurred in ~~Southern~~ southern China The highest value of ε_P mostly occurred in the Huai River basin, the Liao River basin, and the Hai River basin~~,~~, and the lower reaches of Yellow River basin~~.~~, indicating the highest sensitivity of runoff to precipitation change in these regions.

A 1% R_n change may result in ~~caused −0.1~~ −2.1%–0%~~%~~ (−0.5 on average) runoff change. The high value of −~~0.5~~ 2.1 < ε_{R_n} < −~~2.0~~ 0.8 mostly occurred in the Huai River basin, ~~the Liao River basin, and~~ the Hai River basin~~,~~, and the ~~downstream~~ lower reaches of the Yellow River basin, ~~and~~ while the relatively small value of −0.~~1~~ 4 < ε_{R_n} < ~~−0.5~~ 0 mostly occurred in s~~S~~outhern and n~~N~~orthwest China.

The air temperature elasticity, ranging from −0.002/℃~~1~~ to −0.095/℃(−0.025/℃ on average)~~1~~, ~~indicted~~ indicates that a 1 centigrade degree increase in air temperature may ~~will~~ result in a ~~−10~~0.2% –~~10~~9.5% ~~increase~~ decrease in runoff. The high value of −0.095/℃< ε_T < −0.026/℃ mainly occurred in the Songhua River basin, the Liao River basin, the Hai River basin, the lower reaches of the Yellow River basin and the east part of the northwest area; while a small value of −0.025/℃ < ε_T < −0.001/℃ mainly occurred in the south and west regions of China.

The ~~sensibility~~ absolute value of ~~runoff to the~~ air temperature elasticity was small when compared with other elasticities, ~~change varied from geographic position and had no rules, and~~ the reason for which will be discussed~~ in discussion part~~.

The value of ε_{U_2} ranged from −0.01 to −0.94 (−0.22 on average). The high value of −0.95 < ε_{U_2} < −0.5 mostly occurred in the~~-~~Yellow River basin, the Huai River basin, the Hai River basin and the Liao River basin, indicating that a 1% wind speed decrease will lead to a 0.5% – 0.95% decline in runoff.~~north China.~~

The value of ε_{RH} ranged from 0.05 to 3 (0.74 on average), and the spatial distributions of ~~them~~ these values ~~agreed~~ were similar to~~with~~ ~~that~~ those of precipitation.

~~The changes in climatic factors were shown in Fig.5. There is a large spatial variation in precipitation change which increased in the Northwest China (ranging from 5%/decade to 11%/decade, p < 0.05) and decreased in Yellow river basin, Hai River basin and the upper reach of Yangtze River basin (ranging from −5%/decade to −2.5%/decade, p < 0.05), but there were no significant change trend shown in 63% of these 207 catchments.~~

~~Net radiation showed a decrease in most catchments. Large decrease (ranging from −6%/decade to −3%/decade) occurred in the Hai River basin, the Huai River basin and the~~

~~lower reach of Yangtze River basin ($p < 0.05$), while small decrease (ranging from −3%/decade to −0%/decade) occurred in the majority of the Northern China. No significant change trend was shown in the Qinghai-Tibet Plateau.~~

~~Air temperature increased all over the China. Large increase (ranging from 0.4 ℃/decade to 0.8 ℃/decade) mainly occurred in the Northern China ($p < 0.05$), while small decrease (ranging from 0 to 0.4 ℃/decade) occurred in the majority of the Southeast.~~

~~Wind speed decreased in most catchments, ranging from −11%/ decade in the southeast to −1%/decade in the upper reach of Yangtze River basin. Only 5 catchment showed significant ($p < 0.05$) increase in wind.Relative humidity increased in the western China (the maximum is about 3%/decade) and decreased in the Southeast China and the Yangtze River basin (ranging from −1.7%/decade to −0.5%/decade). The change trend of relative humidity agreed with the change of precipitation.~~

4.4 Contributions of climatic factors to ~~the~~ runoff change

Figure ~~5~~5 ~~showed~~ shows the contributions of climatic factors to ~~the~~ runoff change. The contribution of precipitation to the change of runoff ~~had~~ has a distinct spatial variation. ~~Positive~~ A positive contribution occurred in ~~the Western~~ western China and ~~the~~ s~~S~~outheast ~~of~~ China~~ch~~, especially in the ~~Northwest~~ northwest China where the contribution of precipitation to runoff change ranges from 12%/decade to 25%/decade. ~~While negative~~ A negative contribution mainly occurred in ~~the~~ central and northeast China. In the middle reaches of the Yellow River basin and the Hai River basin~~-~~, the negative contribution ~~reaches~~ reached the highest~~most~~, ranging from −18%/decade to −10%/decade.

A p~~P~~ositive contribution of net radiation to runoff change occurred in most catchments, except for the Qinghai-Tibet Plateau. In the Hai River basin, the positive contribution reached the highest~~most~~, ranging from 3%/decade to 9%/decade, compensating to some degree for the decline in runoff caused by precipitation decrease.

~~while in other catchments the net radiation effected the runoff small.~~

~~Positive~~ A negative contribution of air temperature to runoff change occurred in ~~the Qinghai-Tibet Plateau and the northern part of the Northeast~~ all of China. A large contribution (−1% to −3%/decade) mainly occurred in the Songhua River basin, the Liao River basin, the Hai River basin, the lower reaches of the Yellow River basin and the east part of northwest area; while a small contribution (0% to −0.5%/decade) mainly occurred in South China.~~, while negative contribution mainly occurred in Northwest and the Eastern China except for the Northeast China. Positive contribution and negative contribution of air temperature to runoff change were both small when compared with other climatic factors.~~

A ~~Positive~~ positive contribution of wind speed to runoff change occurred in most catchments except for part of the upper reaches of Yangtze River basin. In the Hai River basin and the Liao River basin, the positive contribution reached the highest~~most~~, ranging from 2%/decade to 6%/decade, compensating to some degree for the decline in runoff caused by precipitation decrease.~~while in other catchments the wind speed effected the runoff small~~.

A n~~N~~egative contribution of relative humidity to runoff change occurred in most catchments except for part of ~~the Northwest~~ northwest China where the positive contribution of relative humidity to the change of runoff ranges 0−2%/decade.

~~Figure 7 showed the contribution of climate factors to runoff change, which was defined as the sum of the contribution of climatic factors. Generally speaking, climate change had a negative contribution on runoff in Hai River basin, part of the Liao River basin, the middle and lower reaches of Yellow River basin and the Southeast China, and had a positive contribution in the Northwest, part of the Northeast and the Southeast China. Therein, the largest positive contribution from climate change to runoff occurred in the Northwest, ranging from 10% to 30 %/decade, while the largest negative contribution occurs in the middle reach of the Yellow River basin and the Hai River basin, ranging from −13% to −8%/decade.~~

~~4.5 The dominant climatic factors driving runoff change~~

Figure ~~8~~ 6 ~~showed~~ shows the dominant climatic factors driving runoff in the 207 catchments. In ~~In most~~ 143 of the total 207catchments, the runoff change was dominated by precipitation. In addition, the runoff change was mainly determined by net radiation in some catchments of

~~in~~ the lower reaches of the Yangtze River basin, the Pearl River basin, the Huai River basin and the ~~Southeast~~ southeast ~~Area~~area~~,~~; by air temperature in the upper reaches of the Yellow River basin and the north part of the Songhua River basin; and by wind speed in part of the ~~Northeast~~northeast China, part of ~~the~~ Inner Mongolia ~~and part of the Northeast Area~~.

5 Discussion

5.1 Climate elasticity

The climate elasticity method wa~~i~~s widely used to evaluate the hydrologic cycle in many catchments in China. Tables 4 and 5 show the comparison of our results with estimates of climate elasticities from various references, illustrating good agreement with our results in the same regions.

~~Yang et al. (2014) calibrated precipitation elasticity to be 1.1 to 4.8 in China, which is the same with our result. What's more, in previous study, the precipitation elasticity were evaluated as 2.6 in the Luan River basin (Xu et al., 2013), as 2.4 in the Chao–Bai Rivers basin (Ma et al., 2010), as 1.4 to 1.7 in the Poyang Lake (Sun et al., 2013), as 1.4 for the Beijiang River catchment of the Pearl River basin (Wang et al., 2013), as 1.0–2.0 in the Dongjiang River catchment of the Pearl River basin (Jiang et al., 2007). Those results were also in good agreement with our results for~~ $\cancel{\varepsilon_P}$ ~~in the same regions.~~

~~Wind speed elasticity, which stands for the sensitivity of annual runoff change to wind speed change, was negative across China with small sensitivity in the Southern China and high sensitivity in the Northern China. Yang and Yang (2011) calculated wind speed elasticity~~ $\cancel{\varepsilon_U = -0.3}$ ~~for the Futuo River catchment of the Hai River basin by using the climate elasticity method, which was same with our result for the same catchment. Tang et al. (2013) estimated~~ $\cancel{\varepsilon_u = -0.59}$ ~~for the entire Yellow River basin; Yang and Yang (2011) estimated~~ $\cancel{\varepsilon_U}$ ~~ranging of −0.8 to −0.1 in the 89 catchments of the Hai River and the Yellow River basins of China. Those results were similar to our result in the same regions.~~

~~The net radiation elasticity and the relative humidity elasticity agreed with the result evaluated by Yang and Yang (2011) in Futuo River catchment of the Hai River basin and 89 catchments of the Hai River and the Yellow River basins of China and are also similar to the result calculated by Tang et al. (2013) in the Yellow River basin.~~

In addition, ~~The~~ the air temperature elasticity ~~ranges~~ ranged from −0.002/℃ to −0.095/℃~~−0.1 to 0.1~~, which was~~ere similar to other studies in the same regions (Yang and Yang, 2011;Tang et al., 2013;Yang et al., 2014). However, the air temperature elasticity is~~ obviously smaller ~~when~~ compared ~~to~~ with other climatic elasticities. Next, we will discuss ~~the cause~~ this problem~~why air temperature elasticity is small~~. Air temperature elasticity ~~is~~ was calculated by the following equation:

$$\varepsilon_T=\varepsilon_2\varepsilon_4=\varepsilon_2\frac{1}{\overline{E_0}}\frac{\partial E_0}{\partial T}\Big|_{X=\overline{X}}, \tag{19}$$

where ε_2 ~~is~~ was the runoff elasticity to potential evaporation, ranging from −3 to 0 in China. ~~So the value of ε_T is mainly determined by $\frac{\partial E_0}{\partial T}$. Figure 9 showed the relationship between T and $\frac{\partial E_0}{\partial T}$ in 207 basins of China. $\frac{\partial E_0}{\partial T}$ varied in different basins, but it had increase trend as T increasing. What's more, when T < 10℃, $\frac{\partial E_0}{\partial T}$ was negative mostly, while when T > 10℃, $\frac{\partial E_0}{\partial T}$ was positive mostly.~~ Next, we will analyze the value of $\frac{\partial E_0}{\partial T}$ by the differential method. Denoting Eq. (8) as $E_0=f_1(\Delta,e_s)$,~~and~~ we can express Δ (kPa℃$^{-1}$) and e_s (kPa) as $\Delta=f_2(T)$ and $e_s=f_3(T)$, respectively. Due to their substitution, $\frac{\partial E_0}{\partial T}$ can be expressed as:

$$\frac{\partial E_0}{\partial T}=\frac{\partial E_0}{\partial\Delta}\frac{\partial\Delta}{\partial T}+\frac{\partial E_0}{\partial e_s}\frac{\partial e_s}{\partial T}, \tag{20}$$

where $\frac{\partial E_0}{\partial\Delta}=\frac{\gamma}{(\Delta+\gamma)^2}\left[\frac{(R_n-G)-6.43(1+0.536U_2)(1-RH)e_s}{\lambda}\right]$ and $\frac{\partial E_0}{\partial e_s}=\frac{\gamma}{\Delta+\gamma}6.43(1+0.536U_2)(1-RH)/\lambda$. Figure ~~10~~ 7 show~~ed~~ the trend of Δ and e_s as the change in~~of~~ temperature according to the connection between Δ and T and between e_s and T, where the average values of $\frac{\partial \Delta}{\partial T}$ and $\frac{\partial e_s}{\partial T}$ were 0.0047 and 0.08 in the 207 catchments, respectively.~~.~~Figure 8(A) and (B) show the relationship of $\frac{\partial E_0}{\partial \Delta}$ and $\frac{\partial E_0}{\partial e_s}$ with T in 207 basins of China. -$\frac{\partial E_0}{\partial \Delta}$ ranged~~ranged~~ from −5.5 to 9.3 (0.22 on average), while $\frac{\partial E_0}{\partial e_s}$ which ranged from 0.3 to 1.9 (0.85 on average), decreased with rising air temperature~~ranged from 0.3 to 1.9 (0.85 on average)~~. From the results above, it ~~could~~ can be found that the absolute value of $\frac{\partial E_0}{\partial \Delta}\frac{\partial \Delta}{\partial T}$ was small when compared with $\frac{\partial E_0}{\partial e_s}\frac{\partial e_s}{\partial T}$ due to the small value of $\frac{\partial \Delta}{\partial T}$. $\frac{\partial E_0}{\partial T}$ was mainly determined by $\frac{\partial E_0}{\partial e_s}$, indicating that the rising air temperature mainly affected saturation vapor pressure, leading to changes in potential evaporation. ~~$\frac{\partial E_0}{\partial \Delta}$ and $\frac{\partial E_0}{\partial e_s}$ is small and the sign of $\frac{\partial E_0}{\partial T}$ depends on $\frac{\partial E_0}{\partial \Delta}$. Furthermore, the derivatives Δ and e_s with respect to temperature is small, which leads to the small value of $\frac{\partial E_0}{\partial T}$.~~Based on the results, F~~F~~ig.~~ure~~ 9 show~~ed~~s the relationship between T and $\frac{\partial E_0}{\partial T}$ in 207 basins of China. $\frac{\partial E_0}{\partial T}$ ranged from 0.04 to 0.12 ~~varied~~ in different basins, ~~but~~a ~~it had in~~decrease~~ing~~ trend as T increas~~ing~~ed. ~~What's more, when T < 10℃, $\frac{\partial E_0}{\partial T}$ was negative mostly, while when T > 10℃, $\frac{\partial E_0}{\partial T}$ was positive mostly.~~

~~Changing in air temperature would affect the atmosphere, which results in potential evaporation change, further affecting runoff. What's more changeing air temperature would also affect atmospheric movement, resulting in precipitation change (Gardner, 2009). In fact, changes in air temperature have great effects on runoff. The climate elasticity method only analyzes the direct impact of air temperature on runoff but ignore the indirect impact. Chiew~~

~~et al. (2009) evaluated that the indirect impact of air temperature on runoff would be important, and a degree global warming will result in −10–3% changes in runoff.~~

5.2 Effect of climate change on~~to~~ runoff

~~Recently, many studies have been carried out to assess the effects of climate change on runoff. Xu et al. (2013) reported that the runoff increase caused by cliamte change were 8.8 and 9.2 mm simulated by GBHM and the climate elasticity model in Luan River basin. Tang et al. (2013) analyzed response of natural runoff to climate change in the Yellow River basin by using the climate elasticity method and SWAT model, and the two methods also gave similar conclusion. Their results agreed with that revealed in this study.~~The contribution of climatic factors on runoff change can be estimated by climate elasticity and changes in climatic factors. Significance and rate of changes in climatic factors from 1961 to 2010 have been reported by Yang et al. (2015).

The contribution of precipitation to runoff change has a regional pattern. A large negative contribution mainly occurred in the Hai River basin and the Yellow River basin, and the possible cause was the decrease in precipitation from 1961 to 2010. This decrease may be caused by weakening of the East Asian monsoon circulation (Xu et al.,2006). However, as a result of decreasing atmospheric stability and increasing amounts of transfer of water vapor, a significant increasing trend in precipitation occurred in Xinjiang Province and the Qinghai-Tibet Plateau (Bai and Xu, 2004), further leading to a positive contribution of precipitation to runoff change.

A large positive contrbution of net radiation occurred in the Hai River basin and the Huai River basin, while a small contribution occurred in the Qinghai-Tibet Plateau. The main cause of these results was the spatial variation of the net radiation change. As a result of atmospheric dimming and the increase of atmospheric turbidity, there was an obvious decrease of the surface solar radiation in China, especially in the Hai River basin and the Huai River basin (Tang et al., 2011; Zhao et al.,2006). However, due to the thin and stable air condition, net radiation in Qinghai-Tibet Plateau changed little.

There was a significant warming trend for all of China during 1961–2010 due to human activities, including industrialization and agricultural production (Ren et al.,2012), leading to a negative contribution to runoff change. Remarkably, the climate elasticity method only analyzes the direct impact of air temperature on runoff, i.e., higher temperature leading to larger evaporative demand and further inducing more evaporation (less runoff). In fact, rising temperatures also have indirect impacts on runoff (Gardner, 2009). For example, Chiew et al., (2009) reported that a degree global warming will result in −10 to 3% changes in precipitation in Australia, leading to runoff change.Furthermore, rising air temperatures will lead to a longer snowmelt period, further resulting in an increase in annual runoff (Li et al., 2013).

Due to the changes in atmospheric circulation and surface roughness, a weakening of wind speed has occurred in most regions of China, especially in esatern China where urbanization and environmental changes have taken place rapidly (Vautard et al., 2010). Consequently, the response of runoff to wind speed was intense in the Hai River basin, the Liao River basin and the northeast area, resulting in a large positive contribution of wind speed to runoff change.

A nagetive contribution of relative humidity to runoff change occurred in most regions in China, caused by the trend of relative humidity change. The annual relative humidity exhibited a reducing trend in most parts of China; one of the major causes for the reduction of relative humidity was that the increasing rates of specific humidity were smaller than those of surface saturation specific humidity with the increase of temperature (Song et al., 2012).

Precipitation is an important factor driving runoff change. Precipitation may directly impact the conditions of runoff yield or may affect the water supple conditions of evaporation and further affect runoff. Previous studies reported that precipitation decrease ~~is~~ was the dominant factor of declining runoff in the Futuo River catchment (Yang and Yang, 2011) and the Yellow River basin (Tang et al., 2013), ~~which agreed~~agreeing with our results.

In previous studies, when assessing the impacts of changes in climatic factors on runoff in China, wind speed declines were often identified as being important (Tang et al., 2011;Liu et al., 2014; McVicar et al., ~~(~~2012~~)~~). Wind speed decline tended to result in the decline of actual evapotranspiration and complementary increase of streamflow in wet river basins but ha~~s~~d little impacts in dry basins (Liu et al., 2014), ~~which was~~ similar to our results. Remarkably, in some catchments of the ~~Northeast~~northeast area~~,~~ and ~~the~~ Inner Mongolia ~~and the Northwest Area~~, declining wind speed ~~has~~ had the greatest contribution to runoff change. ~~McVicar et al. (2012) stressed that the impact of wind speed change on actual evapotranspiration and runoff was situation dependent. Wind speed decline tended to result in the decline of actual evapotranspiration and complementary increase of streamflow in wet river basins but has little impacts in dry basins (Liu et al., 2014), which was similar to our results. In previous studies, when assessing the impacts of changes in meteorological factors on runoff in China, wind speed declines were often identified as being important (Tang et al., 2011;Liu et al., 2014). And in the part of the Northeast, part of the Inner Mongolia and part of the northwest area, due to the small hydrology changes and the stable precipitation, wind speed decline became the main contribution factor to runoff change.~~In these catchments, changes in precipitation were minimal and the contribution of precipitation to runoff change was small compared with that of wind speed.

The runoff change was mainly determined by net radiation in some catchments of the lower reaches of the Yangtze River basin, the Pearl River basin, the Huai River basin and the southeast area, and by air temperature in the upper reaches of the Yellow River basin and the north part of the Songhua River basin. In these catchments, the precipitation elasticity was low; the changes were slight; and the contribution of precipitation to runoff was small. However, due to a significant decreasing trend in net radiation or obvious warming, changes in net radiation or air temperature had greater impacts on runoff compares with precipitation.

Remarkably, for a specific catchment, some climatic factors have a positive contribution to runoff, while others have a negative contribution. For example, in the Hai River basin, decreasing precipitation lead to −8–−18%/decade runoff change; at the same time, declining net radiation caused a 2–9%/decade runoff change, and weakening wind speed cuased a 1.5–4.5%/decade runoff change, compensating for the runoff decline caused by decreasing precipitation. Consequently, the runoff decrease due to climate change is 0–9%/decade (Yang et al., 2014). Conversely, in the middle reaches of the Yellow River basin, decreasing precipitation also has a −8–−18%/decade contribution to runoff, but the positive contributions from net radiation and wind speed are less than that in the Hai River basin, which leads to the largest runoff decline, 5–13%/decade in the Hai River basin (Yang et al., 2014).

The dominant climatic factor ~~to~~ driving runoff change was determined by the geographic conditions and climate change. In this study, we analyzed the contribution of climatic factors to runoff change by the climate elasticity method. This method ~~which~~ only ~~stresses~~ focused on the direct impact of climate change on runoff but ~~ignores~~ ignored the ~~relation between~~interaction among the climatic factors. These interaction~~. And the relationship~~ need~~s~~ further study.

5.3 Error analysis

In Eq. (10), the net radiation R_n and the air temperature T were considered as two independent ~~elements~~variables. ~~But in fact~~However, according to Eq. (12) and Eq. (13) the net radiation R_n is associated ~~to~~ with the air temperature T. To verify the impact of the relationship between net radiation and air temperature on Eq. (12), the effect of the change in air temperature to change in net radiation R_n must be evaluated as follows:

$$dR_n = \frac{\Delta R_n}{\Delta T} dT \quad . \tag{21}$$

If the effect of T on R_n ~~was~~ is ignored, the relative error ~~was~~ has been observed to be less than 1% ~~,which was~~,as evaluated by Yang and Yang (2011) in the Futuo River basin.

In addition, Eq. (10) is a first-order approximation, ~~which~~ probably ~~results~~ resulting in errors in the estimating of climate elasticity. Yang et al. (2014) evaluated that when the changes in potential evapotranspiration (ΔE_0) and precipitation (ΔP) are not large, the error of ε_P caused by first-order approximation can be discounted, but the error will increase with ~~changes~~ increasing changes, with a 0.5−5% relative error in ε_P ~~When~~ when ΔP = 10 mm and a 5−50% relative error in ε_P ~~When~~ when ΔP = 100 mm. ~~Bao et al. (2012) estimated that a 100 mm increase in precipitation causes 20% increase in ε_P by adopting the Variable Infiltration Capacity (VIC) model.~~

6 Conclusion

In this study, we used the climate elasticity method to reveal the dominant climatic factor driving annual runoff change ~~over~~ across China. We first validated the climate elasticity method ~~which~~ that was first~~ly~~ derived by Yang and Yang (2011) . On account of China being a vast country with remarkable spatial differences in climate and geographical~~y~~ characteristics, we divided China into 207 catchments~~,~~; ~~and then~~ evaluated the climate elasticity of runoff relative to precipitation, net radiation, air temperature, wind speed and relative humidity~~,~~; and estimated the contribution of ~~climate~~ climatic factors to runoff change for each catchment.

In the 207 catchments, precipitation elasticity, which was low in ~~in S~~southern China ~~or~~ and ~~small~~ part of the ~~Northwest~~ northwest area and high in the Liao River basin, the Hai River basin, and the Huai River basin, ranged from 1.1 to 4.~~75~~8 (2.0 on average). This elasticity means that a 1% change in precipitation will lead to a 1.1%−4.8% change in runoff. The air temperature elasticity, which ranged~~ing~~ from −0.002/℃ to −0.095/℃ (−0.025/℃ on average)~~−0.1 to 0.1.~~, ~~Net~~ net radiation elasticity, which ~~ranges~~ ranged from −0.1 to −2 (−0.5 on average), wind speed elasticity, which ranged from −0.01 to 0.94 (−0.22 on average) and relative humidity elasticity, which ranged from 0.05 to 3 (0.74 on average), had similar distributions ~~with~~ to precipitation elasticity.

A large negative contribution of precipitation to runoff change mainly occurred in the Hai River basin and the Yellow River basin, while a positive contribution occurred in Xinjiang Province and the Qinghai-Tibet Plateau. A large positive contrbution of net radiation occurred in the Hai River basin and the Huai River basin, while a small contribution occurred in the Qinghai-Tibet Plateau. A negative contribution of air temperature to runoff change occurred in all of China. A positive contribution of wind speed to runoff change occurred in most parts of China, while a negative contribution of relative humidity to runoff change occurred in most regions of China. A 5−13%/decade decrease in runoff was caused by climate change in the middle reaches of the Yellow River basin and the Hai River basin (Yang et al., 2014). Specifically, changes in precipitation, air temperature, and relative humidity contributed negative impactson runoff. Simultaneously, declines in net radiation and wind speed had positive impacts on runoff, slowing the overall decline in runoff.

~~There was a large spatial variation in climatic factors change. Precipitation increased in the Northwest China and decreased in Yellow River basin, Hai River basin and the upper reach of Yangtze River basin. Net radiation showed a decrease in most catchments. Air temperature increased all over the China. Wind speed decreased in most catchments and the change of relative humidity agrees with the change of precipitation.~~

~~Climate change had a negative contribution on runoff in part of the Liao River basin, the Hai River basin, the middle and lower reaches of Yellow River basin and the Southeast China, and had a positive contribution in the Northwest, part of the Northeast and the Southeast China. what's more, the largest positive contribution from climate change to runoff ranged from 10% to 30%/decade in the Northwest China, while the largest negative contribution ranged from −13% to −8%/decade in the middle reach of the Yellow River basin and the Hai River basin.~~

~~Regarding~~ Precipitation was the dominant climatic factor~~variable~~ driving runoff change~~, it was precipitation~~ in most of the 207 catchments~~, -~~. ~~net~~ Net radiation was dominant in some catchments of the lower reaches of the Yangtze River basin, the Pearl River basin, the Huai River basin and the southeast area; air temperature was dominant in the upper reaches of the Yellow River basin and the north part of the Songhua River basin; and wind speed in part of the northeast, part of Inner Mongolia.

~~in the lower reach of Yangtze River basin and the Southeast, and wind speed in part of the Northeast.~~

Acknowledgements

This research was partially supported by funding from the National Natural Science Foundation of China (Nos.51379098 and 91225302)~~,~~ and the National Program for Support of Top-notch Young Professionals~~Tsinghua University Initiative Scientific Research Program (20131089284)~~. In addition, this research benefited from the China Meteorological Data Sharing Service System, which provided the meteorological data.

References

Allen, R., Pereira, L., Raes, D., and Smith, M.: Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56., Fao Irrigation & Drainage Paper, 1998.

Angström, A.: Solar and terrestrial radiation, Quarterly Journal of the Royal Meteorological Society, 50, 121-126, 1924.

Arnold, J. G., and Fohrer, N.: SWAT2000: current capabilities and research opportunities in applied watershed modelling, Hydrological Processes, 19, 563-572, 2005.

Arnold, J. G., Srinivasan, R., Muttiah, R. R., and Williams, J. R.: Large hydrologic modeling and assessment Part 1: Model development, J.am.water Resour.assoc, 34, 73–89, 1998.

Arora, V. K.: The use of the aridity index to assess climate change effect on annual runoff, Journal of Hydrology, 265, 164–177, 2002.

Bai, J., and Xu, X.: Atmospheric hydrological budget with its effects over Tibetan plateau, Journal of Geographical Sciences, 14, 81-86, 2004.

Budyko, M. I.: The Heat Balance of the Earth's Surface, Soviet Geography, 2, 3-13, 1961.

Chiew, F., Teng, J., Vaze, J., and Kirono, D.: Influence of global climate model selection on runoff impact assessment, Journal of Hydrology, 379, 172-180, 2009.

Cong, Z., Yang, D., Gao, B., Yang, H., and Hu, H.: Hydrological trend analysis in the Yellow River basin using a distributed hydrological model, Water Resources Research, 45, 335-345, 2009.

Fu, G., Charles, S. P., and Chiew, F. H. S.: A two-parameter climate elasticity of streamflow index to assess climate change effects on annual streamflow, Water Resources Research, 43, W11419, 10.1029/2007WR005890, 2007.

Gardner, L. R.: Assessing the effect of climate change on mean annual runoff, Journal of Hydrology, 379, 351–359, 2009.

Jiang, T., Chen, Y. D., Xu, C. Y., Chen, X., Chen, X., and Singh, V. P.: Comparison of hydrological impacts of climate change simulated by six hydrological models in the Dongjiang Basin, South China, Journal of Hydrology, 336, 316–333, 2007.

Li, B. et al.: Variations of temperature and precipitation of snowmelt period and its effect on runoff in the mountainous areas of Northwest China, Journal of Geographical Sciences, 23, 17-30,2013.

Liu, X., Zhang, X. J., Tang, Q., and Zhang, X. Z.: Effects of surface wind speed decline on modeled hydrological conditions in China, Hydrology & Earth System Sciences, 18, 2803-2813, 2014.

Ma, H., Yang, D., Tan, S. K., Gao, B., and Hu, Q.: Impact of climate variability and human activity on streamflow decrease in the Miyun Reservoir catchment, Journal of Hydrology, 389, 317-324, 2010.

Ma, Z., Kang, S., Zhang, L., Tong, L., and Su, X.: Analysis of impacts of climate variability and human activity on streamflow for a river basin in arid region of Northwest China, Journal of Hydrology, 352, 239-- 249, 2008.

Mcvicar, T. R., Roderick, M. L., Donohue, R. J., and Van Niel, T. G.: Less bluster ahead? Ecohydrological implications of global trends of terrestrial near-surface wind speeds, Ecohydrology, 5, 381–388, 2012.

Penman, H. L.: Natural evaporation from open water, Bare Soil and Grass, Royal Society of London Proceedings, 193, 120-145, 1948.

Ren, G., Ding, Y., Zhao, Z., Zheng, J.,Wu, T., Tang, G. and Xu, Y.: Recent progress in studies of climate change in China, Adv Atmos Sci, 29, 958–977, 2012.

Sankarasubramanian, A., Vogel, R. M., and Limbrunner, J. F.: Climate elasticity of streamflow in the United States, Water Resources Research, 37, 1771–1781, 2001.

Schaake, J. C.: From climate to flow, Climate change and US water resources., edited by: Waggoner, P. E., John Wiley, New York, 177-206 pp., 1990.

Song, Y., Liu, Y., and Ding, Y.: A study of surface humidity changes in china during the recent 50 years, Acta Meteorologica Sinica, 26, 541-553, 2012.

Sun, S., Chen, H., Ju, W., Song, J., Zhang, H., Sun, J., and Fang, Y.: Effects of climate change on annual streamflow using climate elasticity in Poyang Lake Basin, China, Theoretical & Applied Climatology, 112, 169-183, 2013.

Sun, Y., Tian, F., Yang, L., and Hu, H.: Exploring the spatial variability of contributions from climate variation and change in catchment properties to streamflow decrease in a mesoscale basin by three different methods, Journal of Hydrology, 508, 170–180, 2014.

Tang, B., Tong, L., Kang, S., and Zhang, L.: Impacts of climate variability on reference evapotranspiration over 58 years in the Haihe river basin of north China, Agricultural Water Management, 98, 2011.

Tang, Q., Oki, T., Kanae, S., and Hu, H.: The influence of precipitation variability and partial irrigation within grid cells on a hydrological simulation, Journal of Hydrometeorology, 8, 499, 2007.

Tang, W., Yang, K., Qin, J., Cheng, C. and He, J.: Solar radiation trend across China in recent decades: a revisit with quality-controlled data, Atmos Chem Phys, 11, 393–406, 2011.

Tang, Y., Tang, Q., Tian, F., Zhang, Z., and Liu, G.: Responses of natural runoff to recent climatic variations in the Yellow River basin, China, Hydrology & Earth System Sciences, 17, 4471-4480, 2013.

Vautard, R., Cattiaux, J., Yiou, P., Thepaut, J. and Ciais, P.: Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness, Nat Geosci, 3:756–761,2010.

Vogel, R. M., Wilson, I., and Daly, C.: Regional regression models of annual streamflow for The United States, Journal of Irrigation & Drainage Engineering, 125, 148-157, 1999.

Wang, Z., Shen, Y., and Song, L.: Hydrologic response of the climatic change based on SWAT Model in Beijiang River basin, Meteorological & Environmental Research, 8-12, 2013.

Water Resources and Hydropower Planning and Design General Institute, Specification for Comprehensive Water Resources Zoning, China Water & Power Press, Beijing China, 2011.

Xu, M., Chang, C., Fu, C., Qi, Y., Robock, A., Robinson, D. and Zhang, H.: Steady decline of east Asian monsoon winds, 1969–2000: evidence from direct ground measurements of wind speed, J Geophys Res, 111:D24, 2006.

Xu, X., Yang, H., Yang, D., and Ma, H.: Assessing the impacts of climate variability and human activities on annual runoff in the Luan River basin, China, Hydrology Research, 44, 940-952, 2013.

Yang, D., Herath, S., and Musiake, K.: Development of geomorphology-based hydrological model for large catchments, Proceedings of Hydraulic Engineering, 42, 169-174, 1998.

Yang, D., Herath, S., and Musiake, K.: Comparison of different distributed hydrological models for characterization of catchment spatial variability, Hydrological Processes, 14, 403-416, 2000.

Yang, D., Li, C., Hu, H., Lei, Z., Yang, S., Kusuda, T., Koike, T., and Musiake, K.: Analysis of water resources variability in the Yellow River of China during the last half century using historical data, Water Resources Research, 40, 308-322, 2004.

Yang, D., Sun, F., Liu, Z., Cong, Z., and Lei, Z.: Interpreting the complementary relationship in non-humid environments based on the Budyko and Penman hypotheses, Geophysical Research Letters, 33, 122-140, 2006.

Yang, H., Yang, D., Lei, Z., and Sun, F.: New analytical derivation of the mean annual water‐energy balance equation, Water Resources Research, 44, 893-897, 2008.

Yang, H., and Yang, D.: Derivation of climate elasticity of runoff to assess the effects of climate change on annual runoff, Water Resources Research, 47, 197-203, 2011.

Yang, H., Qi, J., Xu, X., Yang, D., and Lv, H.: The regional variation in climate elasticity and climate contribution to runoff across China, Journal of Hydrology, 517, 607–616, 2014.

Yang, H., Yang, D., Hu, Q. and lv, H.: Spatial variability of the trends in climatic variables across China during 1961-2010, Theoretical and Applied Climatology, 120,773-783, 2015.

Zhao, C., Tie, X. and Lin, Y.: Apossible positive feedback of reduction of precipitation and increase in aerosols over eastern central China, Geophys Res Lett, 33, L11814, 2006.

Zheng, H., Lu Zhang, Ruirui Zhu, Changming Liu, Yoshinobu Sato, and Fukushima, Y.: Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin, Water Resources Research, 45, http://dx.doi.org/10.1029/2007WR006665., 2009.

~~Bao, Z., Zhang, J., Liu, J., Wang, G., Yan, X., Wang, X., and Zhang, L.: Sensitivity of hydrological variables to climate change in the Haihe River basin, China, Hydrological Processes, 26, 2294–2306, 2012.~~

~~Kendall, M. G.: Rank correlation methods, Biometrika, 1948.~~

~~Kendall, M. G., J. D.: Rank Correlation Methods, Oxford University Press, Oxford, 1990.~~

~~Maidment, D. R.: Handbook of Hydrology, McGraw-Hill, New York, 1993.~~

Table 1. Principal parameters of the Penman equation

Symbol	Unit	Value	Physical meaning
$\triangle$	kPa ℃$^{-1}$	-	slope of the saturated vapor pressure versus air temperature curve
Rn	MJ m^{-2} d^{-1}	-	net radiation
G	MJ m^{-2} d^{-1}	-	soil heat flux
γ	kPa ℃$^{-1}$	-	psychrometric constant
λ	MJ kg^{-1}	2.45	latent heat of vaporization
e_s	kPa	-	saturated vapor pressure
RH	%	-	relative humidity
U_2	m s^{-1}	-	wind speed at a height of 2m

Table 2. Principal parameters of Eq. (12)

Symbol	Unit	Value	Physical meaning
α_s	dimensionless	-	albedo or the canopy reflection coefficient
R_s	MJ m^{-2} day^{-1}	-	solar radiation
σ	MJ K^{-4} m^{-2} day^{-1}	4.903×10^{-9}	Stefan–Boltzmann constant
T_{max}	℃	-	daily maximum air temperature
T_{min}	℃	-	daily minimum air temperature
n	hour	-	daily actual sunshine duration
N	hour	-	daily maximum possible duration of sunshine
RH	%	-	daily relative humidity

Table 3. Validation of the climate elasticity method~~Comparison between the climate contribution to runoff by using the climate elasticity method and by using the hydrological models~~

Catchments	Upper Bijiang River basin	Upper Luan River basin	Lower Luan River basin	Upper Hanjiang River basin
Study period	1956-2000	1956-2005	1956-2005	1970-2000
$\overline{P}$	495.2	402.4	512.4	850.0
$\overline{E_0}$	1056.9	1257.4	1207.5	1178.0
$\overline{R_0}$	243.4	34	92.6	352
$\Delta P / \overline{P}$	3.9%	−9.8%	1.8%	−11.3%
$\Delta E_0 / \overline{E_0}$	−3.7%	−6.2%	−8.0%	3.0%
ΔR	20.5	−10.1	−29.1	−97.0
$(\Delta R / R)_O$	8.4%	−30.8%	−31.4%	−27.6%
n	0.7	1.4	1.4	1.0
ε_P	1.39	2.2	2.1	1.6
ε_{E_0}	-0.39	−1.2	−1.1	−0.6
$(\Delta R / R)_M$	*	−14.0%	12.4%	−19.6%
$(\Delta R / R)_E$	6.9%	−21.4%	9.1%	−19.0%

* $\overline{P}$ is the mean annual precipitation (mm); $\overline{E_0}$ is mean annual potential evaporation(mm); $\overline{R_0}$ is mean annual runoff (mm); $\Delta P / \overline{P}$ is the percentage of precipitation change (%); $\Delta E_0 / \overline{E_0}$ is the percentage of potential evaporation change; ΔR is the runoff change during the study period (mm); $(\Delta R / \overline{R})_O$ is the percentage of runoff change that was observed; n is the

characteristics parameter; ε_P and ε_{E_0} are the precipitation elasticity and potential evaporation elasticity, respectively; $(\Delta R / R)_M$ and $(\Delta R / R)_E$ are the percentage of runoff change that was estimated by hydrological models and the climate elasticity method, respectively.

Table 4. Comparison of the precipitation elasticity between the reference results and the results from this study

climate elasticity	Study Region	Reference	reference results	results from this study
	the Luan River basin	Xu et al., 2013	2.6	2.5
	the Chao–Bai Rivers basin	Ma et al., 2010	2.4	2.5
	the Poyang Lake	Sun et al., 2013	1.4 to 1.7	1.6
ε_P	the Beijiang River catchment of the Pearl River basin	Wang et al., 2013	1.4	1.4
	the Dongjiang River catchment of the Pearl River basin	Jiang et al., 2007	1.0–2.0	1.4

Table 5. Comparison between the runoff elasticity to climatic factors between the reference results and the results from this study

Study Region		ε_{Rn}	ε_{T}	ε_{U_2}	ε_{RH}	Reference
the Futuo River basin	ε*	−0.79	−0.048	−0.33	0.83	Yang and Yang,2011
	ε	−0.67	−0.047	−0.33	0.80	
the Yellow River basin	ε*	−0.76	−0.046	−0.59	0.78	Tang et al.,2013
	ε	−1.07 to −0.46	−0. 015 to −0.067	−0.55 to −0.1	0.3 to 1.1	
the Hai River basin and the Yellow River basin	ε*	−1.9 to −0.3	−0.02 to −0.11	−0.8 to −0.1	0.2 to 1.9	Yang and Yang,2011
	ε	−2.0 to 0.3	−0.015 to −0.096	−0.85 to −0.1	0.2 to 2.1	

* ε_{Rn}, ε_{T}, ε_{U_2}, and ε_{RH} are the runoff elasticity to net radiation (*Rn*), mean air temperature(*T*), wind speed (*U*), and relative humidity (*RH*), respectively. ε* and ε are results from the references andfrom this study, respectively.

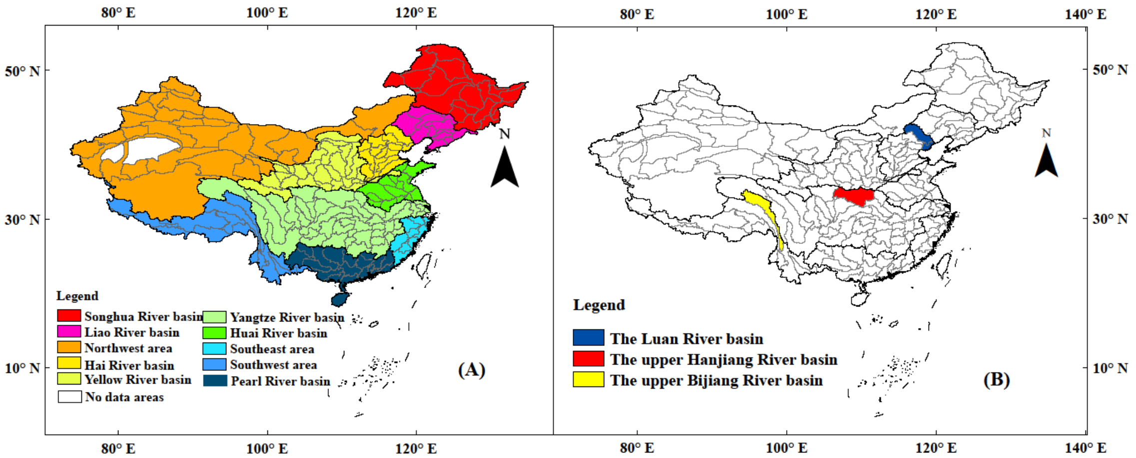


Figure 1. (A) Spatial distribution of ~~the~~ third-level river basins in China and (B) ~~two~~ three catchment~~basin~~s for validation.

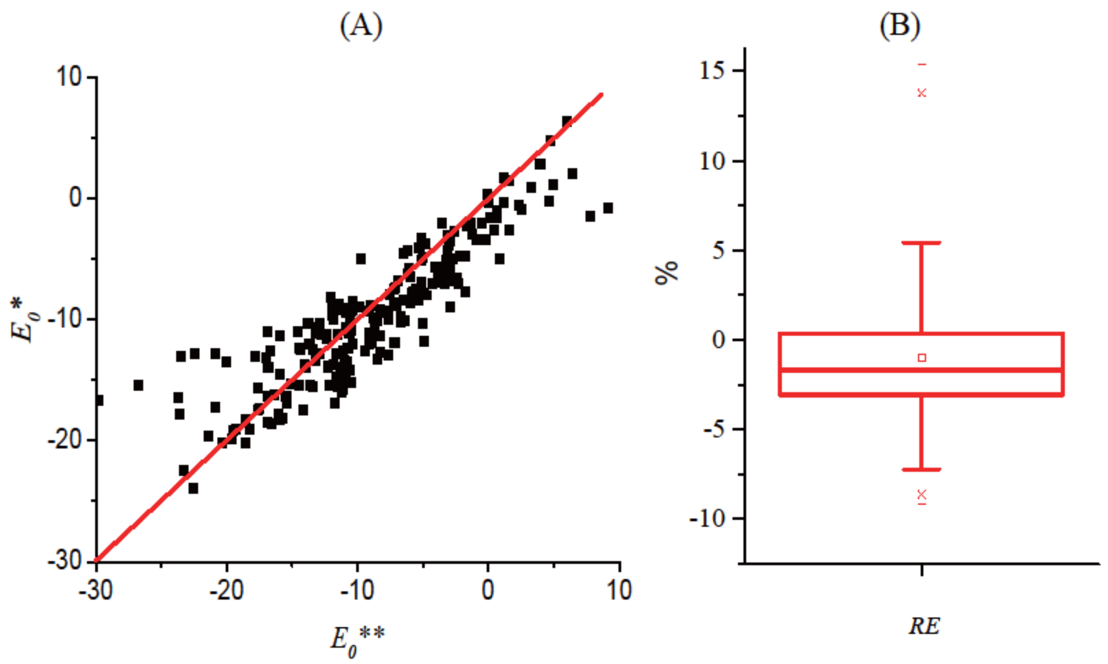


Figure 2. (A) Comparison between the potential evaporation change evaluated by Eq. (9)~~equation (9)~~, denoted as $E_0^*(\%)$, and that evaluated by Eq. (17), ~~equation (17)~~ denoted as $E_0^{**}(\%)$, from 1961–~~-~~2010, and (B) the relative error (*RE*) (%) caused by the first-order approximation, where $RE=(E_0^*-E_0^{**})/E_0^{**}$, E_0^* and E_0^{**} were the potential evaporation changes evaluated by Eq. (9) and Eq. (17), respectively~~-~~.

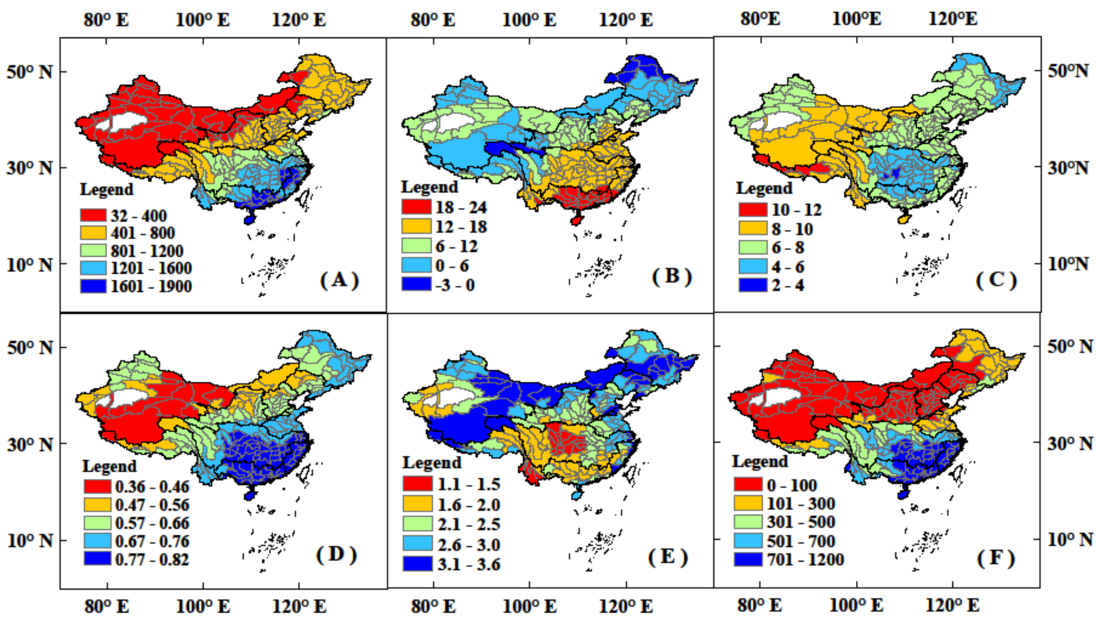
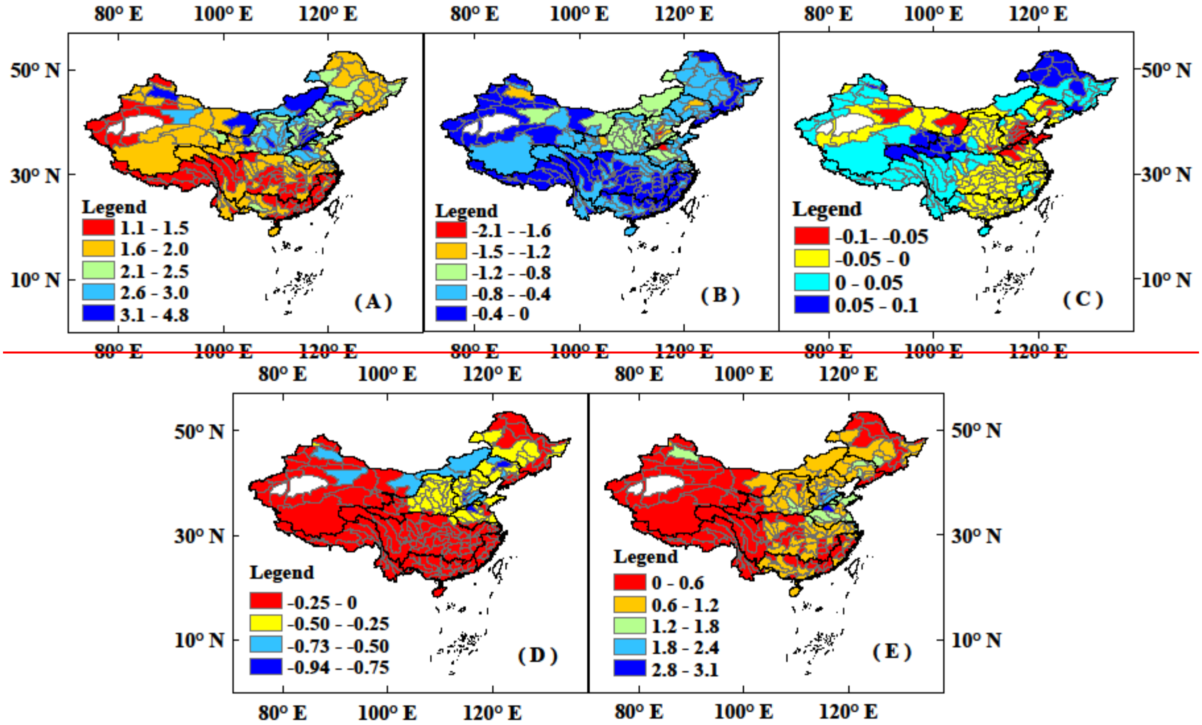


Figure 3. The mean annual (A) precipitation(unit: mm), (B) air temperature (unit: ℃), (C) net radiation (unit: MJ m^{-2} d^{-1}), ~~wind speed,~~ (D) relative humidity, (E) wind speed ~~in~~ at 2m height (unit: m s^{-1}), and (F) runoff (unit: mm) in the 207 catchments during 1961~~-~~–2010.



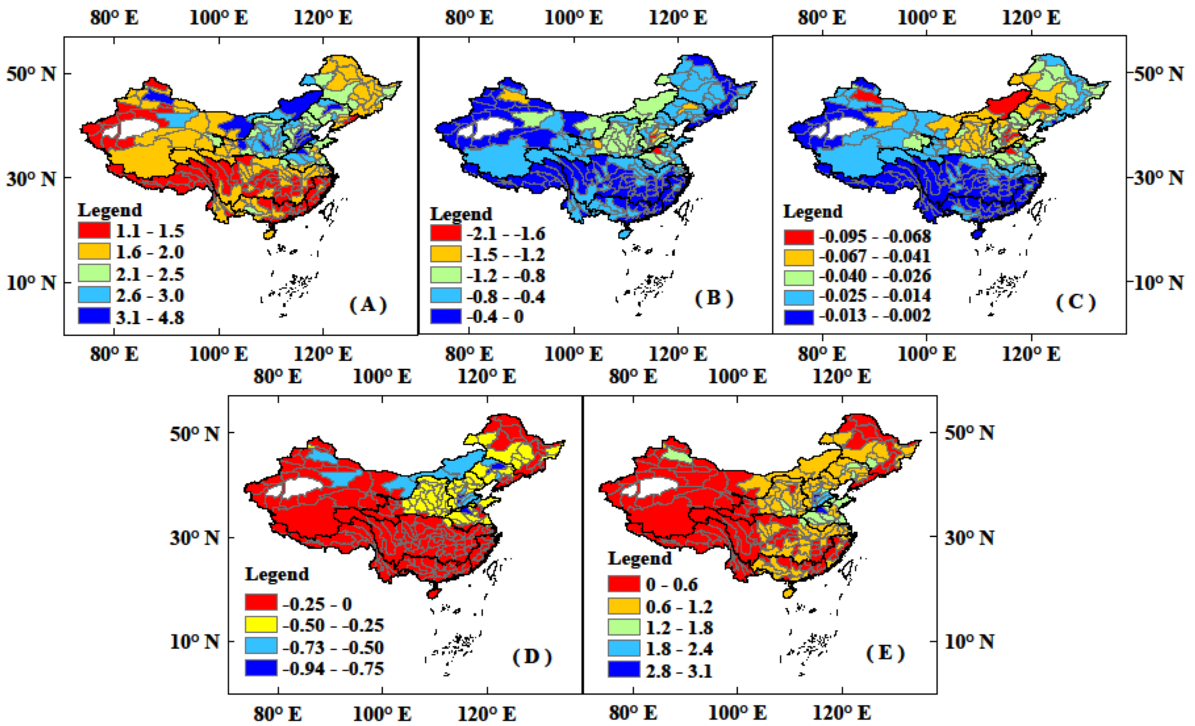
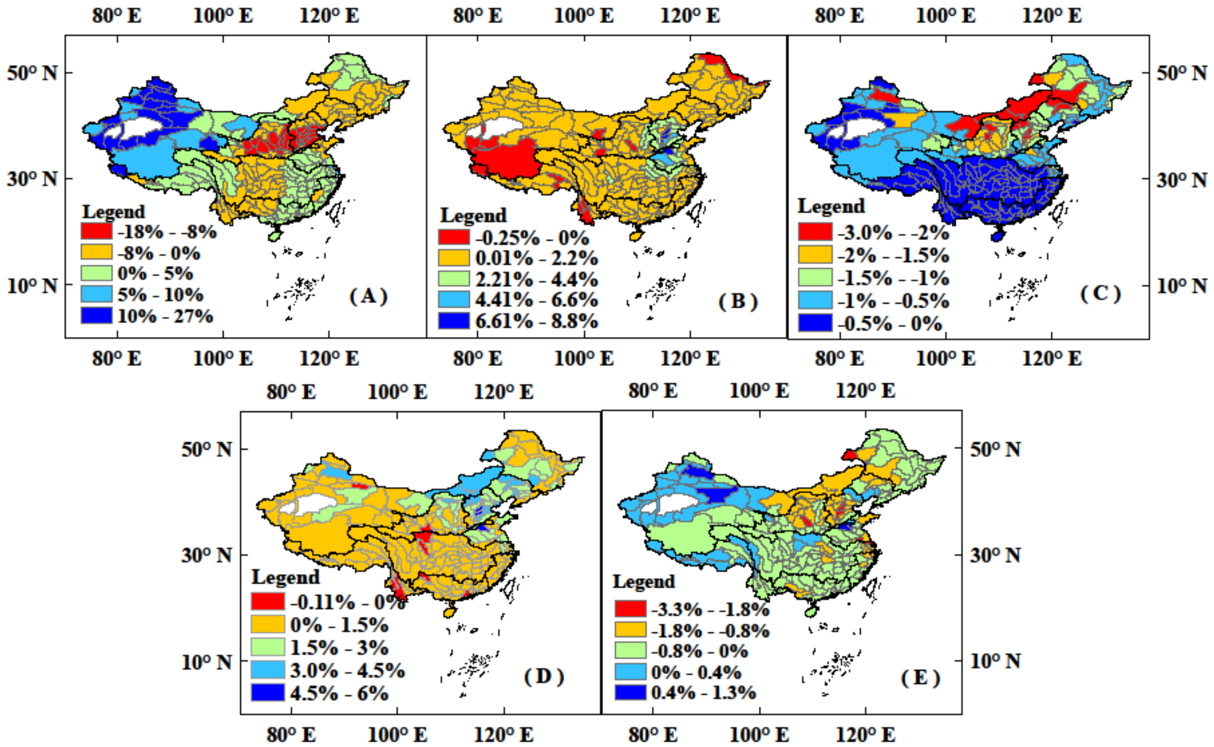
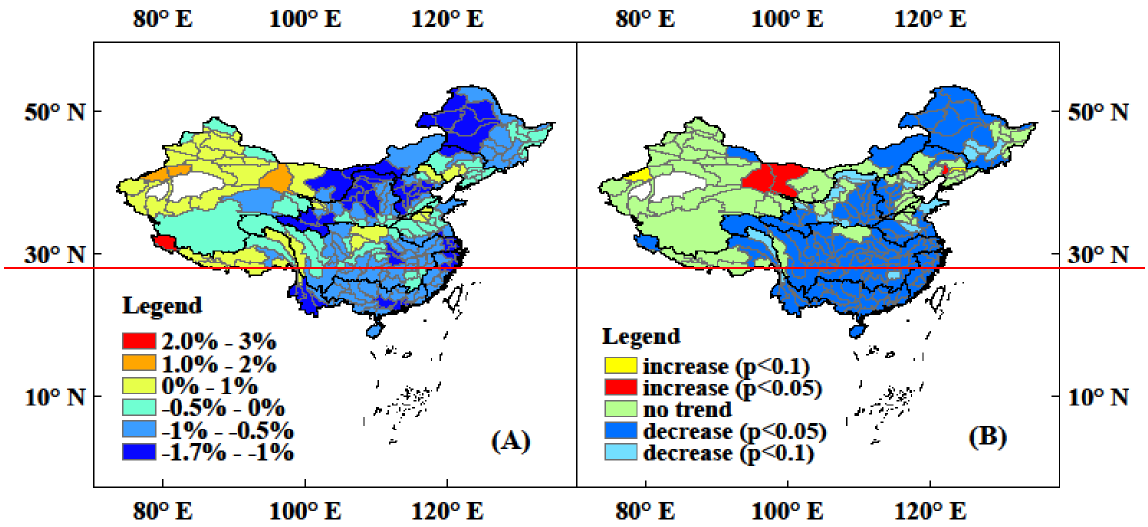


Figure 4. (A) precipitation elasticity ε_P, (B) net radiation elasticity ε_{R_n}, (C) air temperature

elasticity ε_T (unit: /°C), (D) wind speed elasticity ε_{U_2} , and (E) relative humidity elasticity ε_{RH} of runoff in the 207 catchments.





~~Figure 5. The changing trends for (A1) precipitation (unit: /decade), (B1) net radiation (unit: /decade), (C1) air temperature (unit: ℃ /decade), (D1) wind speed (unit: /decade), (E1) relative humidity (unit: /decade); and the significance of the trends for (A2) precipitation, (B2) net radiation, (C2) air temperature, (D2) wind speed, (E2) relative humidity to runoff in the 207 catchments from 1961-2010.~~

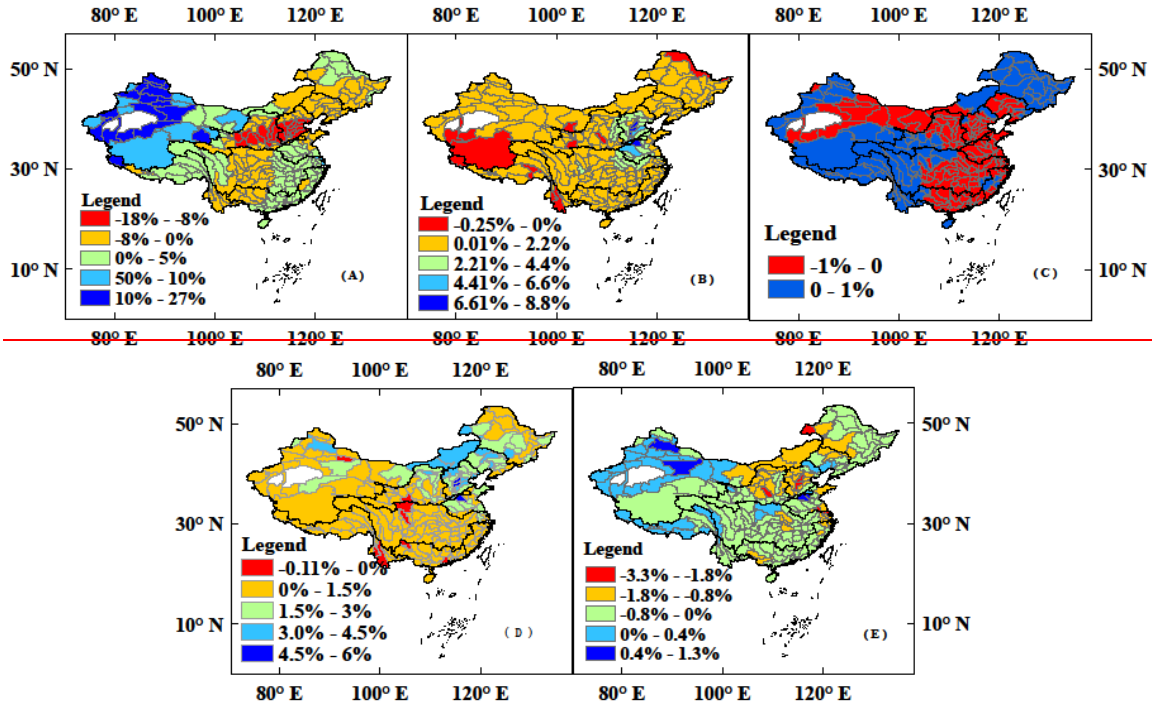
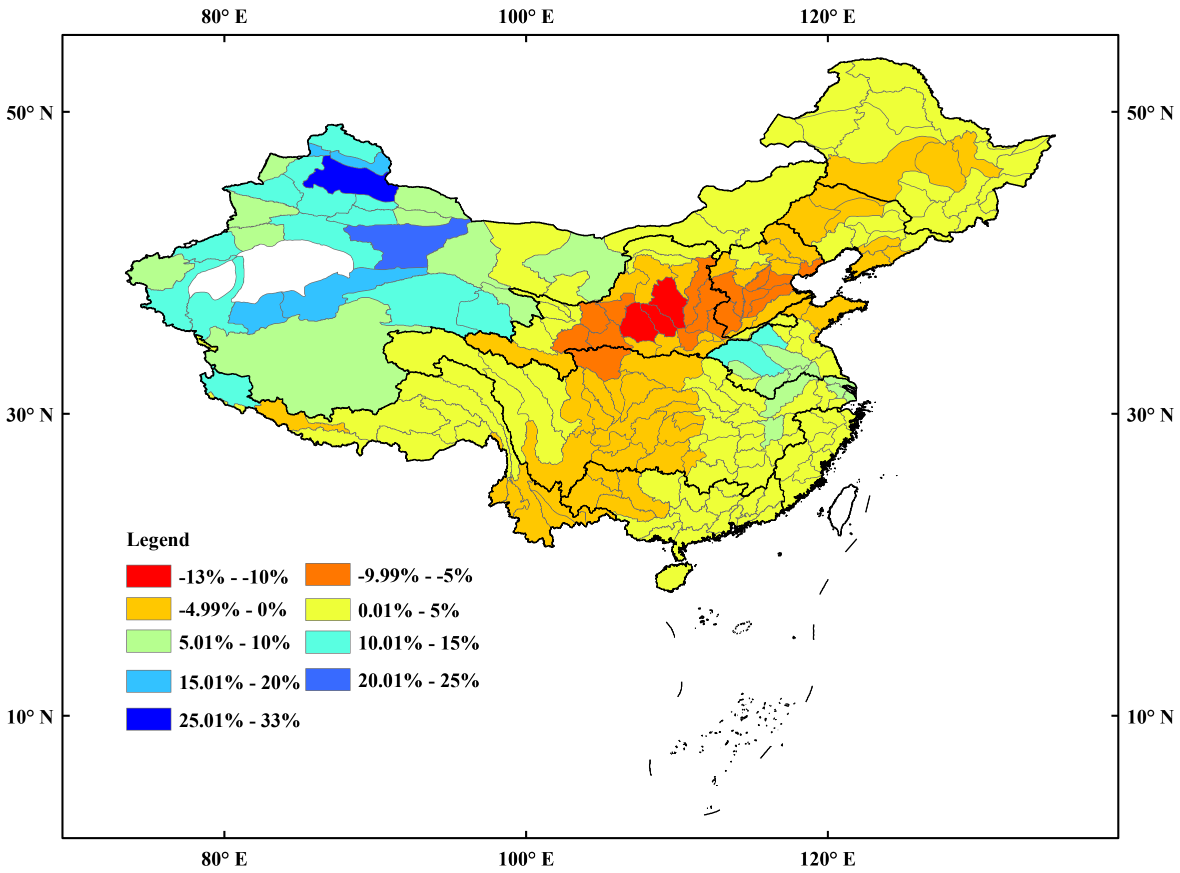
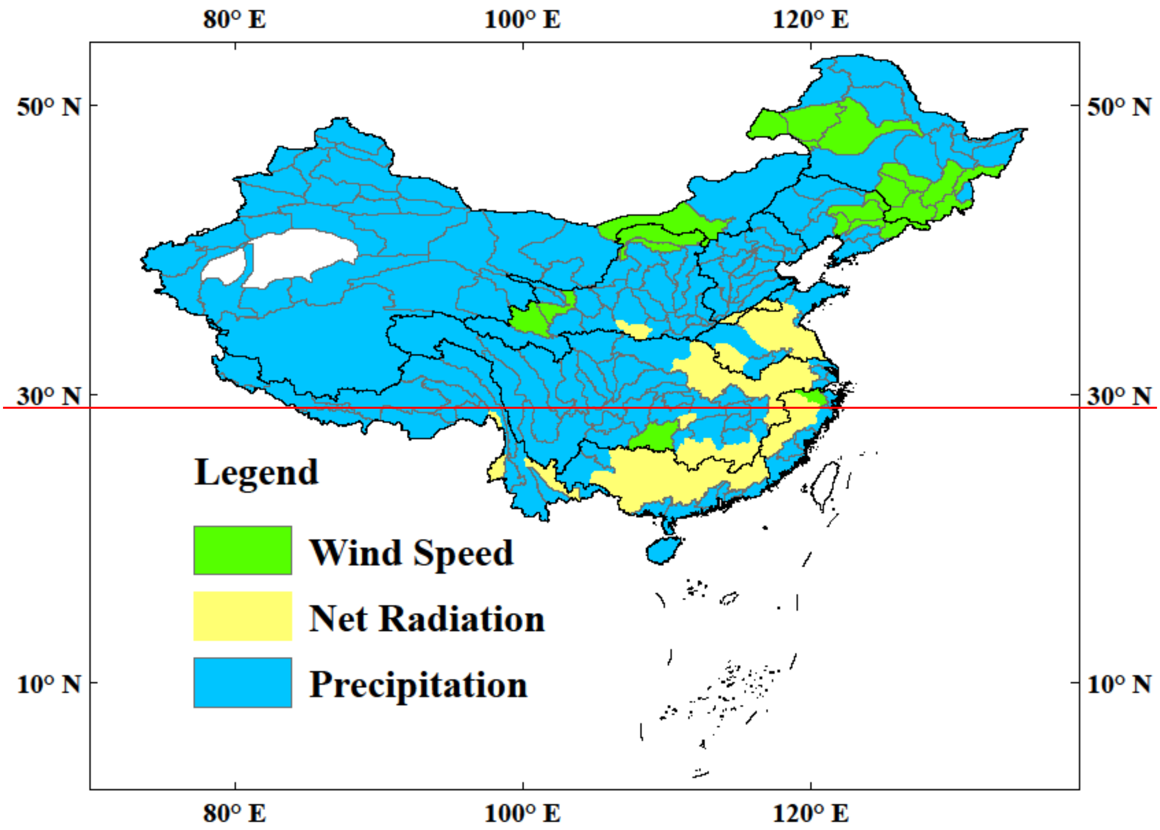


Figure ~~6~~5. The contribution of (A) precipitation, (B) net radiation, (C) air temperature, (D) wind speed, and (E) relative humidity to runoff change in the 207 catchments from 1961~~-~~to 2010 (unit: /decade).



~~Figure 7. The effect of climate change to runoff in the 207 catchments from 1961 to 2010 (unit:/decade).~~


80° E
100° E
120° E
50° N
30° N
10° N
Legend
Wind Speed
Net Radiation
Precipitation

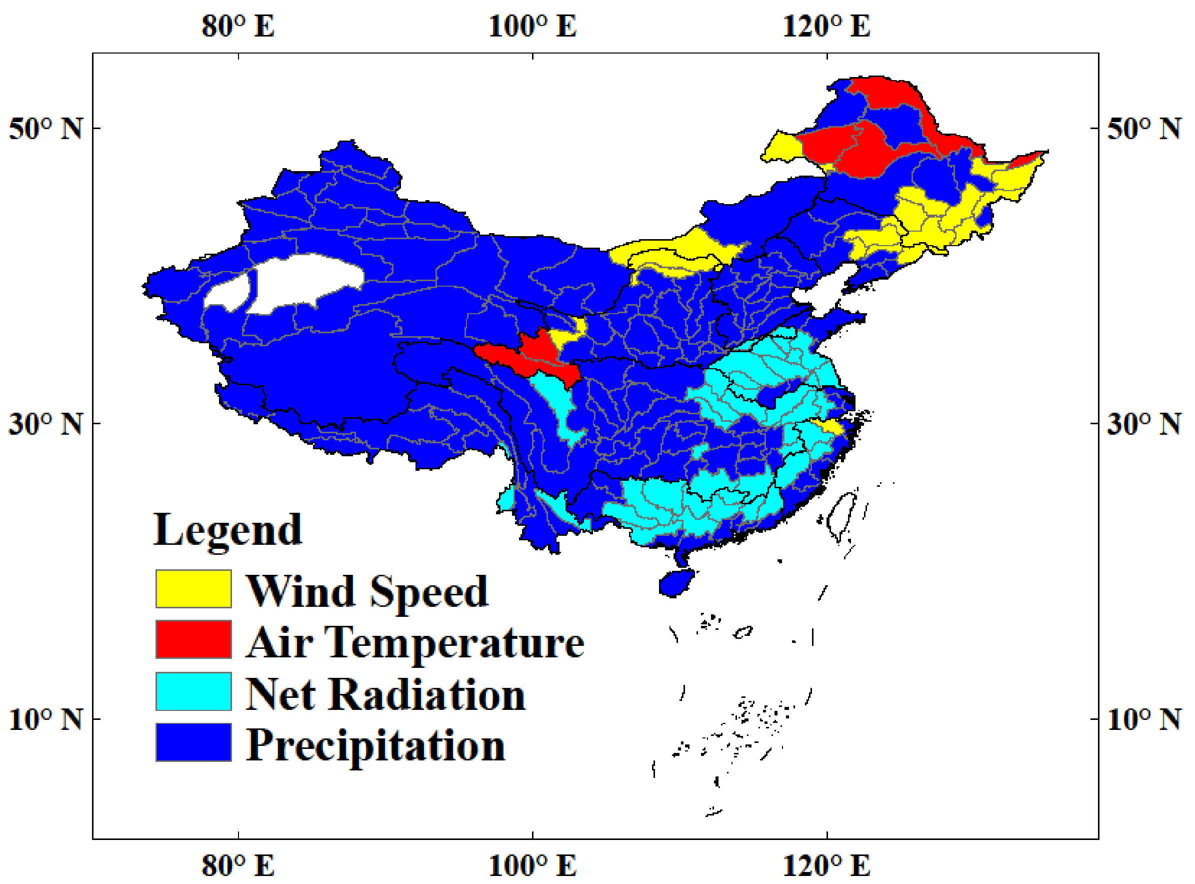
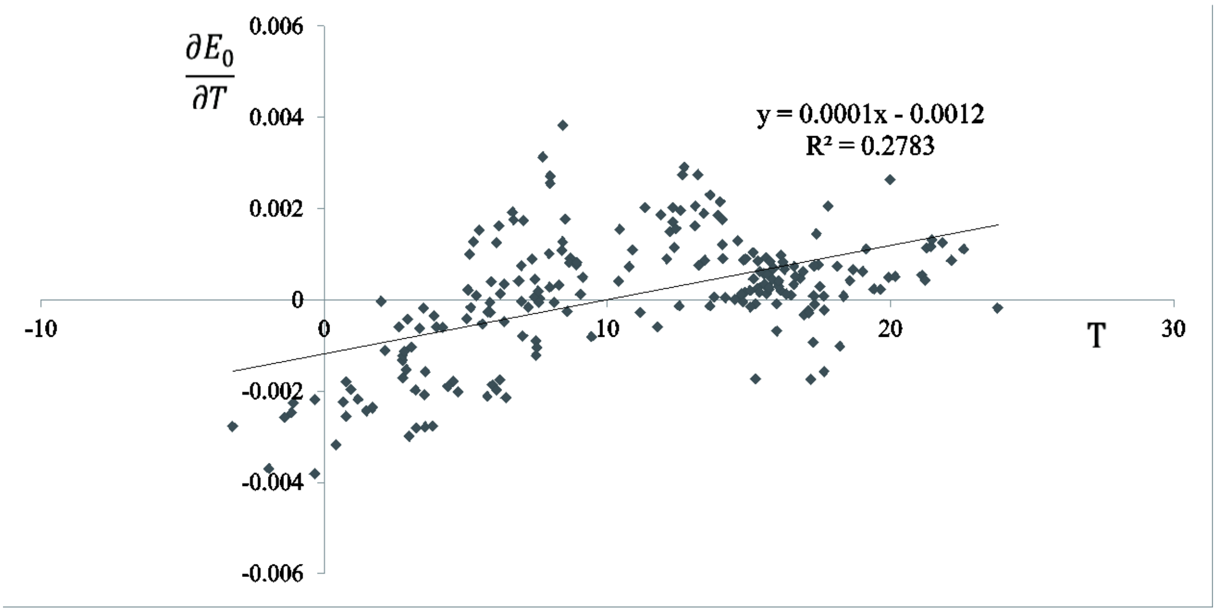


Figure ~~7~~6. Dominant climatic factors driving annual runoff change in the 207 catchments from 1961 to 2010.



~~Figure 9. Relationship between T and $\frac{\partial E_0}{\partial T}$ in the 207 basins of China。~~

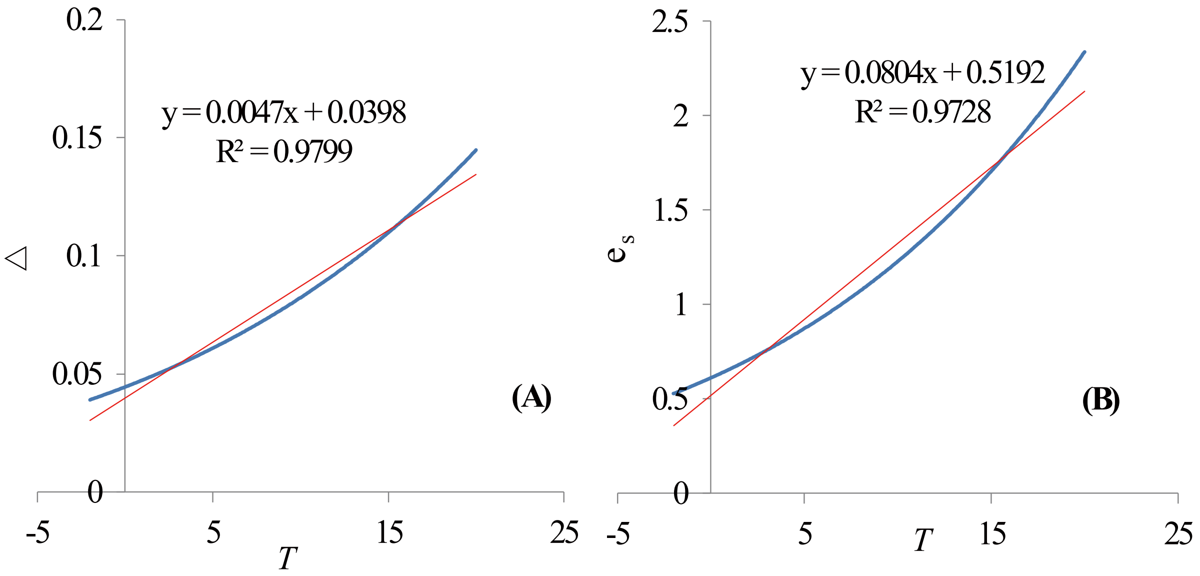


Figure ~~10~~7. The r~~R~~elationship of (A) △(kPa/℃)and (B) e_s (kPa) with temperature *T* (℃) change. The blue curves are the relationship of △ and e_s with *T*, respectively; the pink curves show the linear slope of △ and e_s with *T* (*T* ranging from –~~-~~2 ℃ to 20 ℃), respectively.

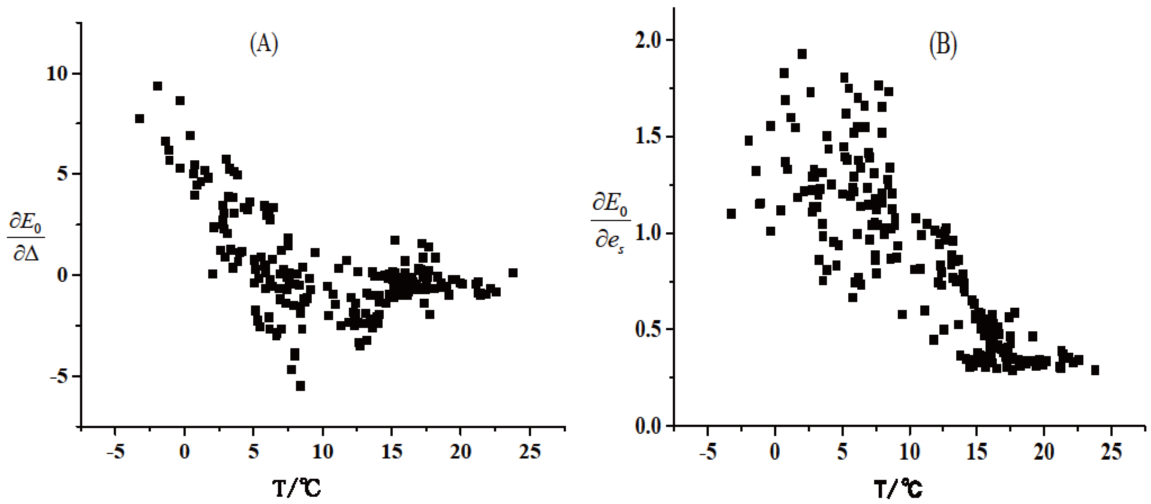


Figure 8. The relationship of (A) $\frac{\partial E_0}{\partial \Delta}$ and (B) $\frac{\partial E_0}{\partial e_s}$ with T, respectively, in the 207 basins of China.

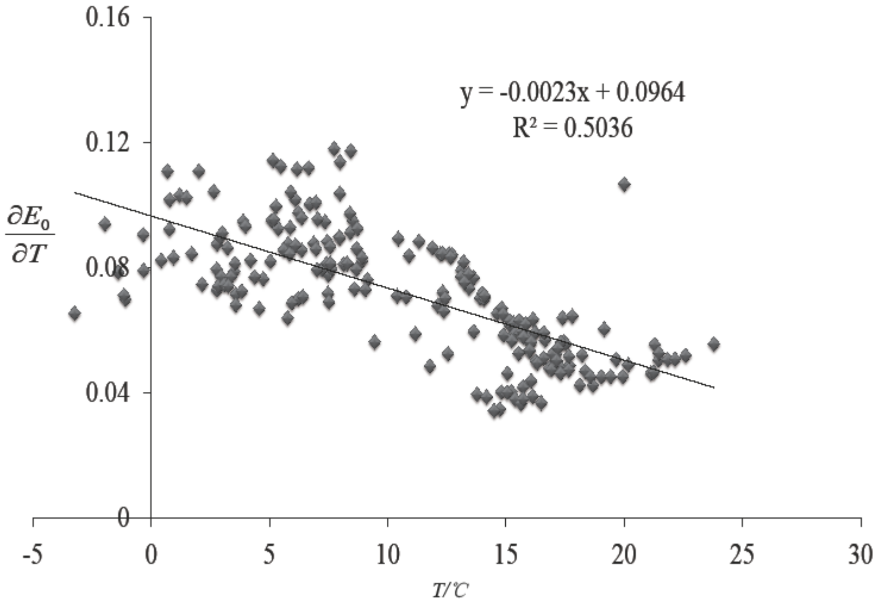


Figure 9. The relationship between $\frac{\partial E_0}{\partial T}$ and T in the 207 basins of China.