

**Response to the Reviews and revised manuscript with marked changes for
'Effects of snow ratio on annual runoff within Budyko framework' by Zhang et
al.**

Manuscript Details:

Effects of snow ratio on annual runoff within Budyko framework (HESS-2014-557)

Authors:

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

Responses to Referee Comments by W.R Berghuijs

Referee comments in Italics

Overview

This paper investigates how snow fraction (mean snowfall rate/mean precipitation rate) influences mean annual runoff, using a Budyko water balance approach for 282 catchments spread across China. The study is presented as an extension of recent work by Berghuijs et al (2014a), who found a strong role for snow fraction on annual runoff based on data from several hundred catchments located across the contiguous United States. The novel aspects of the presented manuscript are:

1. Investigations of the role of snowiness on annual streamflow are performed for a new region (China). This is a relevant contribution as the physical processes that are causing the role of snow for annual streamflow are yet to be clarified. Hence, data driven studies are needed to test if similar behavior is observed in other regions than explored by Berghuijs et al (2014a).

2. An extension of the Budyko framework is presented that takes into account the role of snowfall. Previously the role of snow has not been included in Budyko type studies, but given the role it has on annual streamflow this extension can be considered relevant.

3. An assessment of future streamflow conditions is given based on climate scenarios and the developed Budyko framework with the snow extension. This approach considers the role of changing snow conditions explicitly, and thus these predictions do consider an important aspect of climate change impacts on annual streamflow that previously have mostly been ignored.

The paper thereby potentially makes a valuable contribution to understanding the role of snow for precipitation partitioning into streamflow and evaporation and develops a generally applicable method to address this issue. The topic covered in the paper therefore seems suitable for publication in this special edition of HESS.

However, before publication in HESS a couple of issues need to be addressed. First several of the assumptions underpinning the developed method need to be clarified and limitations of the method need to be better explained and acknowledged. Additionally, the language used in the manuscript is not always fluent and precise, and needs to be improved. I made some suggestions for improvement, but this list is not complete (please notice I am not a native speaker).

We appreciate the reviewer's thoughtful remarks and positive impression of our work. According to the suggestions of the reviewer, we recognize that this work's limitations must be more explicitly stated within the text to ensure that we do not overstate the accomplishments of this analysis. Also, we will thoroughly go through the manuscript and further improved the grammars and wording. We hope our responses to the comments and the changes made to the text will be satisfactory.

Major comments

1. *In your methodology you assume that melting snow water flows away through channels without evaporation loss (Page 947). Subsequently you use this assumption to derive a set of equations that is central to this study. You give several reasons to clarify why this assumption is acceptable (e.g. frozen ground, etc.). However, data clearly suggests that this assumption cannot apply in many regions of the world, and is unlikely to be representative in many other parts of the world.*

For example, in a classification study of Berghuijs et al (2014b) using several hundred MOPEX catchments, many of the catchments classified as snow dominated (snow fraction > 0.45 + aridity (E_p/P) between 0.75-1.75) have a smaller runoff fraction (Q/P) than a snow fraction ($Snow/P$), implying that your assumption cannot be representative in these catchments (even if it is assumed only snow produces runoff, and all rain is evaporated).

Additionally, the catchments studies also expose a strong response in recharge of soil moisture and groundwater after snowmelt, implying that snow rather infiltrates into the ground and later is (at least partly) available for evaporation (e.g. Buttle, 1989; Dripps, 2012; Jasechko et al., 2014).

The above mentioned observations limit the general applicability of your develop framework. Therefore you should (1) clarify the limitations of the applicability of the developed framework in regions where this assumption is wrong, and give an indication of the error this potentially introduces, and (2) indicate under what conditions the framework seems applicable, and under what conditions it is not applicable.

Thanks for the comments by the reviewer. We recognize that the application of this study has its limitation. The assumption that there is no evapotranspiration loss in snowmelt is a compromise between obtaining a concise expression and the lack of understanding on the role of snow on annual water balance at present.

Under the conditions described in Page 947 Lines 16-22, or in some small catchments, after snowfall is melt, the snow water can flow away quickly through channels without evaporation loss. The framework proposed here seems applicable. In fact, it may be more suitable to introduce $k \cdot (1 - r_s) \cdot P$ as “effective available water” for evapotranspiration, where k is a loss parameter need to be further investigated. In the future work, the isotope hydrological method may provide a tool to quantify the parameter for different catchments.

Apart from the above assumption, the accurate estimation of snow ratio is also

important for this framework. However, direct snow observation records are not available for the case study watersheds in this manuscript and the MOPEX watersheds used by Berguhijis et al. (2014). The mean annual snowfall is estimated by empirical method. The threshold temperature is critical for calculating the snowfall amount. A higher threshold temperature will overestimate the snow ratio that may lead to an unreasonable conclusion under the framework in our study.

According to the reviewer's comment and suggestion, we will add a part of discussion on limitation of this framework and future possible work in the revision, as follows:

4.6 limitation of revised Budyko framework

It should be noted that the assumption of no evapotranspiration loss in snowmelt adopted in Section 3.1 is not universally applicable. In small catchments, after snowfall is melt and the concrete frozen ground inhibits snowmelt infiltration, the snow water can flow away quickly through channels without evaporation loss. However, if the location of accumulated snow is far away from channels, or the snowfall amount is large, it will take longer for melt water to run off than the frozen soil thaws. In these cases, a part of snow infiltrates into the ground and later is available for evaporation (Dripps, 2012; Jasechko et al., 2014). In fact, it may be more suitable to introduce $k \cdot (1 - r_s) \cdot P$ as "effective available water" for evapotranspiration, where k is a loss parameter requiring further investigation. To better understand and parameterize the snowmelt loss by evapotranspiration, the site-specific modeling and isotope-based field observations may provide tools for more detailed modeling in the future.

Apart from limitation of the assumption, the accurate estimation of snow ratio is also important for this framework. However, direct snow observation records are not available for the case study watersheds in this manuscript and the MOPEX watersheds used by Berguhijis et al. (2014). Mean annual snowfall is estimated by the air temperature-based empirical method. The threshold temperature is critical for calculating the snowfall amount. A higher threshold temperature will overestimate the snow ratio that may lead to an unreasonable conclusion under the framework in our study. According to the sensitivity analysis of catchment parameter estimation, it shows that a small variation in snow ratio can lead to a significant change in catchment parameter when snow ratio is large enough to be comparable to runoff index. Thus, the accuracy of snow ratio is important to this framework especially when the snow ratio is large, which limits the applicability of this framework in those catchments.

2. *When you attribute runoff changes to snowfall changes (according to your description in section 3.2) several assumptions underpinning this attribution are not discussed/considered:*

You do consider the role of topography and vegetation coverage as potential other secondary controls. Yet, other studies imply that precipitation seasonality and root zone storage capacity are the most important factors (after aridity) for determining annual streamflow (e.g., Milly, 1994; Wolock & McCabe, 1999; Potter et al., 2005; Berghuijs et al., 2014b). Why did you not consider these factors and discuss if it matters that you did not consider for these factors?

Thank you for this comment. As the reviewer stated, it is complex and still not very clear what factors affect the catchment parameter n . The relations between n and precipitation seasonality (sometimes rainfall depth) and root zone storage capacity have been discussed in the literatures (Donohue et al., 2012; Cong et al., 2014). In this paper, we focus on the influence of snowfall on the parameter n . All the discussion about topography and vegetation coverage is to indicate that the influence of snowfall still exists even when the topography or the vegetation coverage is similar. In addition, the vegetation characteristics reflect the information of the precipitation seasonality and root zone storage capacity. Therefore, we did not consider them in this paper, though it is another valuable topic in Budyko's framework.

Refs:

Donohue, R. J., Roderick, M. L., & McVicar, T. R. (2012). Roots, storms and soil pores: Incorporating key ecohydrological processes into Budyko's hydrological model. *Journal of Hydrology*, 436, 35-50.

Cong, Z., Zhang, X., Li, D., Yang, H., & Yang, D. (2015). Understanding hydrological trends by combining the Budyko hypothesis and a stochastic soil moisture model. *Hydrological Sciences Journal*, 60(1), 145-155.

One my main concerns is that snow fraction is both a function of precipitation timing and temperature. This study does not explicitly consider precipitation timing, and consequently all differences in snowfall are attributed to temperature effects. Explain to what degree this may affect your study.

Good catch. Because the observation only records daily precipitation amount, the effect of precipitation timing on snowfall cannot be accessed in this study. And the method to estimate snowfall is also developed base on the same data. Furthermore, the topic here is the impact of mean annual snow ratio on mean annual runoff that is over a much longer time scale compared to precipitation event (daily). Our opinion is that effect of precipitation timing on the study is small.

Although you use a split sample test to check whether the method appears to predict streamflow well (which it does for the historical time series!), attributing these runoff changes relies on the assumption that a spatial pattern (between catchment comparison) is representative for changing conditions at an individual site. The validity of such space-time symmetry using the Budyko framework has been investigated for specific cases using data (e.g., Sivapalan et al., 2011; Carmona et al., 2014) or model output (e.g., Roderick et al, 2014), but I see little evidence that this

space-time symmetry applies (nor is there evidence that it doesn't!) for your analysis. Also given the fact that a new aspect is investigated, the symmetry is a hypothesis rather than something for which is a lot of supporting evidence.

Thanks for your comments. We agree that the space-time symmetry is still a hypothesis to be tested. The study based on it should be checked carefully as the reviewer commented. However, we think runoff change attribution analysis in this study is not based on that hypothesis. As stated in Section 3.2 Page 949 Lines 8-11, the catchment parameters n' of pre- and post-period are estimated by observations and the difference between them is attributed by the change in land cover. In the attribution analysis, we do not assume whether catchment parameters n' are the same in the two periods. In essential, the attribution equation (13) is a perturbation method (or, the first-order Taylor expansion), which is not based on the assumption that both between-catchment variability and between-year variability follow the same Budyko curve (space-time symmetry).

3. It is unclear to me why different E_p approximations have been used for the reconstruction of historical conditions compared to the projection of future conditions. I assume that this is due to data availability. However, this change of E_p approximation potentially strongly influences your future projections of streamflow as E_p method can give very different values (Federer et al., 1997; McMahon et al., 2013). Additionally, is there a reason you choose these E_p methods rather than solely net radiation as originally used by Budyko (1974)?

Thanks for your comments. We estimate E_p by using different methods due to the data availability as the reviewer mentioned. Outputs of most GCMs do not meet the data requirements for calculating E_p by the Penman-FAO equation. The monthly mean temperature is available for every GCM. Meanwhile, the monthly temperature is credible and can be used to calculate E_p by empirical equations, such as the Hamon's equation.

We agree with the reviewer that E_p values vary with estimation methods. Therefore, we conduct parameter calibration for each catchment to minimize the difference between two E_p estimation methods. We will explain how to do it in detail when replying to Comment #6.

We do not think there is much more difference between using E_p and net radiation. In Section 3.1, we employ the concept of "effective energy available for evapotranspiration" to account for the effect of snow on actual evaporation. It is more straight-forward and well-understood to use E_p to reflect evaporation capacity rather than net radiation.

4. Precipitation is prone to under catch in snowy regions, and precipitation approximates often have largest biases in mountain ranges. What role do such potential biases play in your study?

Good point. As the reviewer mentioned, the accurate areal precipitation estimation is

difficult to measure in mountainous catchments. The effect of potential biases on some flood events is significant. As for the mean annual water balance, as considered in this study, the effect may be less significant. What's more, how to evaluate the role of potential biases is out of scope of our study. What we did is collecting as many meteorological stations with precipitation records as we can to obtain more accurate estimation of areal precipitation.

5. *Are there any other studies that provide a prediction of runoff changes China for similar future scenarios? If yes, how do they compare and can you better emphasise your novel contribution?*

Good points. There are some related studied on runoff changes as mentioned in page953: Lines 27-28. The mountainous catchments show significant increasing runoff, partly caused by increasing snowfall, which is consistent with the analysis in our work. More other studies will be included to enrich the discussion according to the reviewer's suggestion. To our knowledge, almost all other studies are based on distributed hydrological models coupled with GCMs outputs whose shortcomings are specified in Introduction section.

6. *Page 945: Line 10-11 How do you calculate this adjustment parameter and where does this parameter comes from? This needs to be 100% clear as this parameter strongly controls your prediction of future conditions.*

Yes. We agree with the reviewer that the accurate estimation of the parameter is important to prediction of future available energy for evapotranspiration, E_p .

As stated in Page 945: Lines10-11, we calculated mean annual E_p (2000-2010) by averaging daily values obtained by the Penman-FAO equation for each catchment. Meanwhile, we calculated mean annual E_p (2000-2010) by averaging monthly values obtained by the Hamon's equation for each catchment. The adjustment parameter is calibrated by minimizing the difference between the two mean annual E_p s. The calibration was conducted for each catchment. Therefore, each catchment has its own adjustment parameter which is used to predict future conditions.

7. *The simplification from Eq. 10 to Eq. 11 gets inaccurate for catchments with a high snow ratio. Hence, the presented simplified method does not seem applicable to places with a high snowfall rate. Is this already a problem in your analysis for the more snowy catchments and is this a problem when somebody tries to apply the method in a region where most of the precipitation falls as snow?*

This simplification indeed causes inaccurate values. However, we think it may not result in a big difference. Eq. (10) can be reorganized as:

$$\frac{P-Q}{(1-r_s) \cdot P} = [1 + (\frac{E_p}{(1-r_s) \cdot P} - \frac{0.14r_s}{1-r_s})^{-n'}]^{-1/n'}$$

$$\frac{P-Q}{P} = [(1-r_s)^{-n'} + (\frac{E_p}{P} - 0.14r_s)^{-n'}]^{-1/n'}$$

When most of the precipitation falls as snow, assuming $r_s = 0.9$, then $0.14r_s = 0.126$.

Given that $E_p / P \sim 1.5$, the relative error (RE) resulting from the simplification is

$$RE = \frac{0.14r_s}{E_p / P - 0.14r_s} = 9.17\% . \text{ The RE increases with increasing } r_s . \text{ A large } r_s \text{ of } 0.9,$$

which we think is seldom seen in real catchment, only leads to RE less than 10%. So we think this simplification is acceptable.

Thanks for pointing this out. This comment helps us look into the simplification more carefully.

8. *You argue that your quantification of the sensitivity of annual runoff to snow ratio is more robust than by assuming linear correlation between these two variables as by Berghuijs et al. (2014a). However one could also argue (and maybe I am biased as I am the author of the other paper) that using historical variability to approximate future streamflow conditions is much more reliable than relying on the list of assumptions that your method needs. Therefore I am not sure if your claim for being a more robust method than the method of Berghuijs et al is actually valid.*

Agreed. The wording in discussion paper is inappropriate. We will rephrase the relevant sentences and change Page 951 Lines14-16 it to:

“What’s more, quantifying the sensitivity of annual runoff to snow ratio using a new approach based on the Budyko hypothesis may provide more insight into this phenomenon”

9. *You state that the study of Berghuijs et al (2014a) does not provide mechanistic understanding at the catchment scale, which is a motivation for your study. Yet, the only mechanistic explanation you give is by making assumptions about how the system functions. In many ways it seems your study is still an empirical framework, that doesn’t tell us why runoff changes occur under changing snow conditions. Can you better emphasise what we learnt about the mechanistic explanation compared to Berghuijs et al. (2014a)?*

Thanks for this comment. The work by *Berghuijs et al. 2014* did inspire us a lot to put

forward this study. We will be more positive when citing the relevant work in the revision.

In this study we aim to provide more insight into quantifying the relationship between annual runoff and snow ratio using a new analytical approach based on the Budyko hypothesis. The concept of “effective” water/energy available for evapotranspiration was proposed to account for the impact of snow on mean annual actual evapotranspiration. Our study made some progress in mechanistic understanding more or less, although gaps still persist.

10. Considering all the above points, you need to better emphasise the novel contributions and the limitations of your paper.

Agreed. Discussions on the limitation will be added in the revision, as in reply to Comment 1.

Technical comments

1. *Page 940: Line 2: Replace "winter" by "cold season" or remove the word "winter" because snowfall might also be in autumn and spring, and the precipitation state (snow/rain ratio) of these periods is probably most sensitive to temperature changes.*

Yes, "cold season" would be better here.

2. *Page 940: Line 4: replace "but tends", by "but also tends"*

Agreed. The change will be made.

3. *Page 940: Line 20: Replace "winter" by "cold season" or remove the word "winter" because snowfall might also be in autumn and spring, and the precipitation state (snow/rain ratio) of these periods is probably most sensitive to temperature changes.*

Agreed. The change will be made.

4. *Page 940: Line 21: Unclear what you exactly mean by "Fluctuations in snow amount"; are these snowfall changes, snow storage changes, or both? And what do you exactly mean by "fluctuations" in this case?*

Sorry for the confusion. We have hanged "Fluctuations in snow amount" to "Decrease in snowfall amount"

5. *Page 941: Line 12: Unclear what you exactly mean by "the climate change impact".*

We have changed this statement as "hydrological response to snow variation induced by climate change"

6. *Page 941: Line 16: What do you mean by "localization of distributed models"?*

It means site-specific nature of distributed models. For instance, a specific distributed model may perform well in humid area, while poor in arid area for its model framework, runoff generation regime, etc. So, the detailed distributed model may have its best performance under some specific conditions.

7. *Page 941: Line 17: Can you specify what the "large knowledge gaps" are?*

Change "Page 941: Lines 15-18" to:

However, large numbers of parameters and localization of distributed models limit us to clarify the dominant factors affecting the connection between snow ratio and runoff. Furthermore, the distributed model may perform well over short time scales, and large knowledge gaps still remain at multi-annual time scale that impede the pursuit of better understanding the effect of snow ratio on mean annual runoff.

8. Page 941: Line 21: Replace "new" by "alternative".

Agreed. The change will be made.

9. Page 942: Line 21-22: Unclear what you mean by "all observed data being constrained by water and energy limits"

It means that mean annual actual ET is smaller than potential ET and streamflow is smaller than precipitation for all catchments.

Considering: All observed points are within the supply and demand limits of the framework.

10. Page 943: Line 3: Unclear what you mean by "is not available at all the above . . ." is the data not available at any of these stations or is it available at some of them?

The record of precipitation type is available before 1979, but there is no record of precipitation type for all stations since 1980. Therefore, Ding et al., 2014 developed an empirical scheme to discriminate the precipitation type. This method was employed in the study to determinates the state of precipitation and calculate the mean annual snowfall.

11. Page 943: Line 19: "by averaging the values of grids covering the analyzed catchments". Does this mean that if 1% of a gridcell covers a catchment it equally contributes to the rainfall rate of this location as a gridcell that for 100% is located in the catchment?

Yes. Because the Angular Distance-Weighted interpolation used in this study (sorry for mistake in Page 943, Line 18) will produce smooth and even grid data (temperature, precipitation, etc.) and the grid resolution of 10×10 km is also sufficient enough for most catchments, we think error introduced by this method is acceptable.

12. Page 943: Line 20 "The interpolated grid temperature was modified by its elevation". How is this exactly done?

The gradient for change of temperature with elevation was estimated by fitting the relationship between observed temperature of stations which are used to calculate the targeting grid value and its elevation. Then the temperature of targeting grid was modified by grid-averaged elevation according to the gradient.

13. Page 943: Line 22: How are gridcells "water" and "non-waters" defined. Is a gridcell classified as one of them based on the percentage of landcover? If yes, what is this percentage?

Yes. If more than 50% of the gridcell is water, then this gridcell is defined as water. Otherwise, the gridcell is thought as non-waters.

14. Page 944: *It is not clear to me where the net radiation values used in Equation 2&3 have been obtained.*

Thanks for pointing out. The radiation data is recorded in 118 of 743 meteorological stations. We estimated solar radiation using the Angstrom equation (Allen et al., 1998). The parameters in that equation were calibrated using the observed data for each month at the 118 stations with solar radiation observations, and their values for each grid were obtained from the nearest station. We will add this statement to “data sources” section in the revision.

[Ref] Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Papers, 56. Food and Agriculture Organization, Rome.

15. Page 944: *Line 4-8: you forgot the description and unit of T.*

Thanks for pointing out. We will add this described in the revision.

16. Page 944: *Line 17: replace “(M)is” by “(M) is”*

Thanks for pointing out. A space is needed here.

17. Page 947: *Line 8: Does “a rough algebraic computation” results in the exact or approximate solution for Equation 9?*

According to Eq.(8) and relevant parameters (Page 946 :Lines 24-25, Page 947: Lines 1-7),

$$R_m / L = \rho_w W (h_f + C_i \overline{\Delta T}) \approx 1 \cdot (r_s \cdot P) \cdot (335 + 2.1 \times 10) / 2500 = 0.14 r_s \cdot P$$

Thus, Eq.(9) is an approximate solution.

18. Page 950: *Lines 7-8: It is unclear how you derive that “On the whole, the observed data is consistent with the curve pattern”. Do you mean that the points are within the supply and demand limits of the framework?*

The scatter of all 282 points follows the pattern of non-parameter Budyko curve which is similar to the curve derived with $n \approx 1.9$. But a more significant spread can be seen here compared to the analysis by Berghuijs et al., 2014. This sentence may make readers confused. We will delete it in the revision. Thanks reviewer’s comment.

Response to Referee Comments by Anonymous Referee #2

Referee comments in Italics

General comments

This study provides an analytical extension of Budyko framework to account for the role of snow on annual water balance at the catchment scale, validates this extension in China against historical observations, and predicts the future streamflow based on CMIP5 projected forcings and this new extension. I feel that this is a very valuable contribution to catchment hydrology in general and this special issue in particular. The analysis is overall robust and the logic of presentation flows well. The writing could be improved further as pointed out by the 1st reviewer, although I think it is already good enough for most of the readers to easily follow.

We thank a lot the reviewer for the positive comments. According to the suggestions of the reviewer, we will thoroughly go through the manuscript and further improve the grammars and wording.

Specific comments

- 1. A friendly suggestion: be more positive when citing/referring to a very relevant work by Berghuijs et al., 2014, which no doubt has a lot of merits. For example, at Page 941, L5, you could state that "Berghuijs et al. 2014 show that higher snowfall fraction is statistically associated with increased annual streamflow at pristine catchments, but they also pointed out that mechanistic understanding of this phenomenon is still lacking", and "inspired by Berghuijs et al. 2014, in this study we aim to provide more insight into this phenomenon using a new analytical approach based on the Budyko hypothesis". At Page951, L16, you could say that you are providing another way to quantify the sensitivity of annual runoff to snow ratio etc.*

Thanks for suggestions of the reviewer. The work by Berghuijs et al. 2014 did inspire us a lot to put forward this study. We are more positive when citing the relevant work in the revision according to the advices.

- 2. P947, L18. Please rephrase for better readability.*

Agreed. We changed it into: Given that the frozen ground has extremely low permeability, the surface flow is preferred during the snow melting period (Dunne and Black, 1971).

- 3. Fig. 7, the quality of this figure, including legend, is really poor. Please improve.*

Thanks for your comments. We will submit high-quality figures for satisfying the publishing requirement of HESS in the revision.

4. P947, L22, please pay great attention to the preciseness of the language when you are introducing a key assumption. In your study, most of the snow ratio values fall within 0.10, so it is likely that your assumption is only valid when snow ratio is significant but small enough. Reviewer 1 did point to significant evap. loss when snow ratio is high (0.4 or larger) in MOPEX basins. Even further, I believe adding some discussion on the limitations of your current work and possible directions of improvements in the last section, as suggested by Reviewer 1, would in fact enhance your paper.

Good point. We acknowledge that the assumption that there is no evap. loss proposed in P947, L22 is ideal. This simple assumption is a compromise between obtaining a concise expression and our lack of understanding on the role of snow on annual water balance at present. When snow ratio is not very large, the error introduced can be negligible. When the snow ratio is large, this assumption may be out of place. In the revision, we have added some discussion on the limitation of this assumption and the potential efforts to improve the proposed Budyko framework in the last section.

4.6 limitation of revised Budyko framework

It should be noted that the assumption of no evapotranspiration loss in snowmelt adopted in Section 3.1 is not universally applicable. In small catchments, after snowfall is melt and the concrete frozen ground inhibits snowmelt infiltration, the snow water can flow away quickly through channels without evaporation loss. However, if the location of accumulated snow is far away from channels, or the snowfall amount is large, it will take longer for melt water to run off than the frozen soil thaws. In these cases, a part of snow infiltrates into the ground and later is available for evaporation (Dripps, 2012; Jasechko et al., 2014). In fact, it may be more suitable to introduce $k \cdot (1 - r_s) \cdot P$ as “effective available water” for evapotranspiration, where k is a loss parameter requiring further investigation. To better understand and parameterize the snowmelt loss by evapotranspiration, the site-specific modeling and isotope-based field observations may provide tools for more detailed modeling in the future.

Apart from limitation of the assumption, the accurate estimation of snow ratio is also important for this framework. However, direct snow observation records are not available for the case study watersheds in this manuscript and the MOPEX watersheds used by Berguijjs et al. (2014). Mean annual snowfall is estimated by the air temperature-based empirical method. The threshold temperature is critical for calculating the snowfall amount. A higher threshold temperature will overestimate the snow ratio that may lead to an unreasonable conclusion under the framework in our study. According to the sensitivity analysis of catchment parameter estimation, it shows that a small variation in snow ratio can lead to a significant change in catchment parameter when snow ratio is large enough to be comparable to runoff index. Thus, the

accuracy of snow ratio is important to this framework especially when the snow ratio is large, which limits the applicability of this framework in those catchments.

1 **Effects of snow ratio on annual runoff within Budyko framework**

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6

1 **Abstract**

2 | Warmer climate may lead to less ~~winter~~-precipitation falling as snow in cold season.

3 Such a switch in the state of precipitation not only alters temporal distribution of

4 | intra-annual runoff, but also tends to yield less total annual runoff. Long-term water

5 balance for 282 catchments across China is investigated, showing that decreasing

6 snow ratio reduces annual runoff for a given total precipitation. Within the Budyko

7 framework, we develop an equation to quantify the relationship between snow ratio

8 and annual runoff from a water-energy balance viewpoint. Based on the proposed

9 equation, attribution of runoff change during past several decades and possible runoff

10 change induced by projected snow ratio change using climate experiment outputs

11 archived in the Coupled Model Intercomparison Project Phase 5 are analyzed. Results

12 | indicate that annual runoff in northwestern mountainous and northern high-latitude

13 areas are sensitive to snow ratio change. The proposed model is applicable to other

14 catchments easily and quantitatively for analyzing the effects of possible change in

15 snow ratio on available water resources and evaluating the vulnerability of catchments

16 to climate change.

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18 **Keywords:** Budyko framework, snow ratio, runoff, climate change

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1 **1 Introduction**

2 More than one-sixth of the world's population lives in catchments with
3 snowmelt-dominated runoff (Barnett et al., 2005), and thus change in snowfall may
4 exerts a great influence over available water resources in these regions. In a warmer
5 climate, the rising temperature may decrease the precipitation falling as snow in cold
6 season~~winter~~. Decrease in snowfall amount~~Fluctuations in snow amount~~ and
7 increasing in temperature can lead to ~~an~~ earlier spring peak river runoff and a
8 reduction in summer-autumn runoff for a given total annual precipitation (Stewart et
9 al., 2005; Godsey et al., 2014). Therefore, the change in the state of precipitation
10 (rainfall or snow) induced by global warming would alter the temporal distribution of
11 intra-annual runoff, thereby increasing the possibility of spring flood disasters
12 (Allamano et al., 2009) and summer water supply crisis in relevant regions. Although
13 the possible events can have catastrophic impacts on those snow-dominated basins,
14 these impacts can be mitigated where existing reservoirs possess adequate storage
15 capacity to buffer the shift in runoff timing (Vörösmarty et al., 1997; Payne et al.,
16 2004). To date, however, little work has been done to investigate the impact and
17 mechanism of this shift in the state of precipitation on mean annual runoff which is a
18 key factor that controls the available freshwater resources for domestic and
19 agricultural needs. Berghuijs et al. (2014) conducted a preliminary analysis using the
20 MOPEX dataset and found that higher snowfall fraction is statistically associated with
21 increased annual runoff at pristine catchments.~~larger snow fraction leads to a higher~~

1 annual runoff. But the work is limited to presenting observations, without providing
2 the mechanistic understanding at the catchment scale. They also pointed out that
3 mechanistic understanding of this phenomenon is still lacking. ~~To date, however, little~~
4 ~~work has been done to investigate the impact and mechanism of this shift in the state~~
5 ~~of precipitation on mean annual runoff which is a key factor that controls the available~~
6 ~~freshwater resources for domestic and agricultural needs.~~ Inspired by Berghuijs et al.
7 (2014), we aim to ~~This motivates the effort to~~ understand and quantify the relationship
8 between snow ratio, ~~defined as of~~ precipitation falling as snow to total precipitation,
9 and mean annual runoff, as well as assess the hydrological response to snow ratio
10 variation induced by climate change ~~climate change impact in this study.~~

11 In order to address the problem, adopting a distributed hydrological model coupled
12 with Global Circulation Model projections and calibrated with observed data may be a
13 way (Cayan et al., 2008; Huss et al., 2008). However, large numbers of parameters
14 and the site-specific nature ~~localization~~ of distributed models limit us to clarify the
15 dominant factors affecting the connection between snow ratio and mean annual runoff,
16 ~~and large knowledge gaps that impede the pursuit of better understanding their~~
17 ~~relationship still remain.~~ Furthermore, the distributed model may perform well over
18 short time scales, but large knowledge gaps still remain at multi-annual time scale that
19 impede the pursuit of better understanding the effect of snow ratio on mean annual
20 runoff. Meanwhile, it can be a very tedious exercise when quantifying the impact of
21 snow ratio change on the mean annual runoff by applying a detailed hydrologic model

1 to hundreds of catchments.

2 | Low-dimensional models may provide us ~~a new~~ an alternative tool to isolate the key
3 component of the relationship between the above two variables. Budyko (1974)
4 introduced a simplified analytical framework to quantify the long-term averaged
5 | hydrological partitioning between runoff and evapotranspiration at ~~the~~ catchment
6 scale. Within this framework, the actual evapotranspiration (E) is determined, to first
7 order, by available energy and available water which are measured as potential
8 evapotranspiration (E_p) and precipitation (P), respectively. Subsequently, lots of
9 efforts (Fu, 1981; Choudhury, 1999; Yang et al., 2008) focus on theoretical and
10 empirical development of the framework by introducing an additional parameter
11 accounting for local landscape characteristics (Yang et al., 2009) or seasonality of
12 climate forcing (Feng et al., 2012). This simple framework captures the main features
13 of water-energy balance and is widely employed to evaluate the hydrologic response
14 to climate change and human activities (Roderick and Farquhar, 2011; Wang and
15 Hejazi, 2011). When addressing the influence of snow ratio on the mean annual runoff,
16 | the water-energy balance is also the key point which needs to be clarified. Thus, it is a
17 possible way to investigate the influence of snow ratio on mean annual runoff in the
18 | context of the Budyko framework.

19 Here, we study the effects of snow on the mean annual runoff by analyzing the
20 long-term observed records from catchments across China. A theoretical tool is
21 proposed to help us have a deeper understanding of the role of snow on the mean

1 annual runoff quantitatively. In addition, the contributions of changes in snow ratio to
2 the variations in annual runoff during the past several decades and possible changes in
3 annual runoff under projected climate scenario are also presented. Such studies are
4 expected to ~~present~~have important implications for future water management strategy
5 when global warming is considered.

6 **2 Data sources**

7 The daily meteorological data, including precipitation, temperature, relative
8 humidity, wind speed and sunshine hours were collected at 743 national
9 meteorological stations during ~~1956~~1961-2010 from the China Meteorological
10 Administration. In addition, daily solar radiation was collected from 118 stations
11 during the period 1961–2010. Meanwhile, monthly runoff data of 282 catchments
12 across China ~~were~~was collected. These catchments were selected based on the length
13 of records exceeding 25 years and all observed points being within the supply and
14 demand limits of the framework~~all observed data being constrained by water and~~
15 energy limits. Furthermore, there is relatively low direct influence of human activities
16 such as, irrigation, damming, and water diversion on the catchments. The areas of
17 these catchments vary from 372 to 142963 km² and these catchments cover a sizable
18 portion of land area within China as shown in Fig.1. The catchment average slope ~~is~~
19 was calculated from the HYDRO1k data sets, developed ~~at~~by the U.S. Geological
20 Survey's (USGS) EROS Data Center, at a resolution of 1 km. (available at the web
21 <http://eros.usgs.gov/elevation-products>~~http://eros.usgs.gov/#Find_Data/Products_and~~

1 [Data Available/gtopo30/README](#))

2 Because the ~~data of~~ precipitation type is not available at ~~all the above~~ any of the
3 meteorological stations since ~~1979~~ 1980, the empirical relationship evaluated for
4 China territory to discriminate precipitation types is called for. The empirical
5 discrimination scheme [Ding et al., 2014] derived from more than 400,000 samples
6 collected from different climate regimes and elevations across China from 1951 to
7 1979 was adopted. The precipitation is categorized according to:

$$type = \begin{cases} snow, & T_w \leq T_1 \\ sleet, & T_1 \leq T_w \leq T_2 \\ rain, & T_w \geq T_2 \end{cases} \quad (1)$$

8 where T_w is daily mean wet-bulb temperature, a function of air temperature, relative
9 humidity and air pressure. T_1 and T_2 are two threshold temperature which can be
10 empirically parameterized by relative humidity and elevation based on the
11 observations. According to this discrimination scheme, ~~when-if~~ a precipitation event ~~is~~
12 was judged as snow or sleet, the corresponding precipitation ~~magnitude-quantity is~~
13 was counted in the annual snowfall amount.

14 To obtain the average daily climate forcing in each catchment, a 10-km grid data
15 across the China was interpolated from the observations of all ~~the~~ meteorological
16 stations by angular distance-weighted interpolation ~~inverse distance weighting method~~,
17 and then catchment values were calculated by averaging ~~the~~ values of grids covering
18 the analyzed catchments. The interpolated grid temperature was modified by its
19 elevation. Daily E_p ~~is~~ was calculated based on the Penman-FAO equation (Allen et

1 al., 1998) using ~~the~~ grid data with consideration of the corresponding land use type.
 2 And the E_p of grids which are waters and non-waters ~~are-were~~ calculated using Eq.
 3 (2) and Eq. (3), respectively.

$$E_p = \frac{\Delta}{\Delta + \gamma} \frac{R_n - G}{\lambda} + \frac{\Delta}{\Delta + \gamma} \frac{6.43(1 + 0.536U_2)(e_s - e_a)}{\lambda} \quad (2)$$

$$E_p = 0.408 \frac{\Delta}{\Delta + \gamma^*} (R_n - G) + \frac{\gamma}{\Delta + \gamma^*} \frac{900}{T + 273} U_2 (e_s - e_a) \quad (3)$$

4 where T is daily average air temperature [°C] and Δ is the slope of the saturated
 5 vapor pressure versus ~~air temperature~~T curve [kPa ~~°C~~K⁻¹]; U_2 is the wind speed at
 6 2m above ground [m s⁻¹]; e_s is the saturated vapor pressure [kPa]; e_a is the actual
 7 vapor pressure [kPa]; R_n and G are the net radiation and ground heat flux,
 8 respectively [MJ m⁻² d⁻¹]; λ is the latent heat of vaporization of water [J g⁻¹] and γ
 9 is the psychrometric constant [kPa ~~°C~~K⁻¹], $\gamma^* = \gamma(1 + 0.34U_2)$.

10 The daily climate variables ~~are-were~~ aggregated to annual values for all catchments.
 11 Snow ratio (r_s) ~~is-was~~ calculated as the ratio of mean annual snowfall amount to mean
 12 annual precipitation, which can eliminate the influence of phase difference originating
 13 from the snow accumulation and melting in different years.

14 The monthly Global Inventory Modeling and Mapping Studies normalized
 15 difference vegetation index (NDVI) from 1982 to 2006 with 8 km resolution was
 16 collected from the Advanced Very High Resolution Radiometer (AVHRR) sensor
 17 (Buermann et al., 2002). Likewise, long-term average annual NDVI value for each
 18 catchment ~~is-was~~ calculated from the dataset and the corresponding vegetation
 19 coverage (M) ~~is-was~~ estimated following Gutman and Ignatov (1998),

$$M = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \quad (4)$$

1 where $NDVI_{\max}$ and $NDVI_{\min}$ are the NDVI signals from dense green vegetation
 2 and bare soil, which ~~are~~ were chosen to be 0.80 and 0.05, respectively (Yang et al.,
 3 2009).

4 The future climate forcing, monthly precipitation, temperature and snowfall
 5 outputs of all the available ~~climate change~~ experiments from two Representative
 6 Concentration Pathways (RCPs) archived in the Coupled Model Intercomparison
 7 Project Phase 5 (CMIP5) (Taylor et al., 2012) were extracted (38 GCMs for RCP4.5;
 8 40 GCMs for RCP8.5, as shown in Table 1). For each GCM and each RCP, the
 9 precipitation, temperature, and snowfall outputs at the archived spatial resolution were
 10 regridded to $0.5^{\circ} \times 0.5^{\circ}$ grid cells. For each catchment, the monthly areal averaged
 11 precipitation, temperature and snowfall from 2050 to 2099 were calculated from
 12 above model outputs. Monthly E_p was computed using the Hamon's equation
 13 (Hamon, 1961) as:

$$E_p = \alpha \cdot d \cdot D^2 \cdot \rho_w \quad (5)$$

14 where, d is the number of days in a month; D is the mean monthly hours of daylight in
 15 units of 12 h; $\rho_w = 0.0495e^{0.062T}$ is a saturated water vapor density; and T is the
 16 monthly mean temperature [$^{\circ}\text{C}$]. α ~~is an~~ the adjustment factor, ~~which~~
 17 using local historical observations (2000-2010) via minimizing the difference between
 18 the two mean annual E_p values (2000-2010) obtained by the Penman-FAO and
 19 Hamon's equation respectively for each catchment. The projected monthly

1 precipitation, snowfall and potential evapotranspiration were aggregated to annual
2 values for 2050-2099.

3 **3 Methodology**

4 **3.1 Inclusion of snow ratio in the Budyko framework**

5 At multi-decades timescale, neglecting the catchment groundwater or glacial
6 storage change, mean annual actual evapotranspiration (E) is estimated as the
7 residual of annual precipitation minus runoff (Q). On the other hand, E can be given
8 by a function of available energy (E_p) and available water (P) for evapotranspiration,
9 proposed by Budyko (1974):

$$1 - \frac{Q}{P} = \sqrt{\frac{E_p}{P} [1 - \exp(-\frac{E_p}{P})] \tanh(\frac{1}{E_p / P})} \quad (6)$$

10 Other Budyko-type curves were developed for describing catchment long-term
11 water balance, by introducing a unique parameter to assess differences among
12 catchments (Fu, 1981; Choudhury, 1999; Zhang et al., 2001; Wang and Tang, 2014).

13 Among them, Yang et al. (2008) provided a theoretical solution to the mean annual
14 water-energy balance equation under general conditions through dimensional analysis
15 and mathematic reasoning, which shares the same functional form with Choudhury's
16 equation:

$$1 - \frac{Q}{P} = [1 + (\frac{E_p}{P})^{-n}]^{-1/n} \quad (7)$$

17 where, n is a synthesis parameter which represents the effects of catchment factor,
18 such as vegetation type and coverage, soil type and topography, on the precipitation

1 partitioning, referred as specific catchment parameter herein. As shown in Fig.2, the
 2 relationship between annual mean runoff index (Q/P) and dryness index (E_p/P) is
 3 depicted. A larger value of n is associated with a lower runoff index given the same
 4 dryness ~~index-condition~~.

5 When snowfall is considered, there are some differences in energy and water terms
 6 involved in Eq. (7). For evapotranspiration capacity, it should be noted that part of
 7 available energy need be taken away to melt the snowfall compared with “paired
 8 catchment” where other conditions are the same but all precipitation falls as rainfall.
 9 Meanwhile, little sublimation and runoff are observed during snow accumulation
 10 season (Anderson, 1968; Dewalle and Meiman, 1971; Weller and Holmgren, 1974).
 11 The snowfall needs to be transferred into liquid phase before it can participate into the
 12 hydrological cycle. The melting energy R_m required to convert snowfall to the
 13 reference state (0 °C liquid phase) reads:

$$R_m = \rho_w W (h_f + C_i \overline{\Delta T}) \quad (8)$$

14 where, ρ_w is the density of water [1000 kg m⁻³] and W is snow water equivalence
 15 [m], *i.e.* snowfall amount ($r_s \cdot P$); h_f is the latent heat of fusion [335kJ kg⁻¹]. $C_i \overline{\Delta T}$
 16 represents the energy needed in snow warming phase during which the averaged
 17 accumulated snow temperature increases until the snowpack is isothermal at 0 °C
 18 where C_i is the specific heat of ice [2.1kJ kg⁻¹ °C⁻¹] and $\overline{\Delta T}$ averaged negative
 19 snow surface temperature, order of 10 °C.

20 Thus, the effective energy available for evapotranspiration E_p^e is the difference

1 between E_p and melting heat equivalence R_m / L , where L is latent heat of
2 evaporation [2500kJ kg^{-1}]. After a rough algebraic computation, E_p^e reads:

$$E_p^e = E_p - R_m / L = E_p - 0.14r_s \cdot P \quad (9)$$

3 In melting season, the magnitude of sensible heat is several times larger than latent
4 heat (Dingman, 2002), implying that only a small part of snow is evaporated or
5 sublimated. For example, according to the energy budget during the accumulation and
6 melt periods for 6 seasons (1968-1973) at the Danwille site, VT, US (Anderson,1976),
7 the average turbulent exchange of latent heat each season are 1160cal/cm^2 , equivalent
8 to 1.7cm vaporized water. Compared with the maximum snow depth of 72cm in that
9 location, the evaporation of snowfall is very small.

10 What is more, the concrete frozen ground is most commonly found in open land
11 and sometimes in forested land (Pierce et al., 1958; Fahey and Lang, 1975), which
12 makes the melting water infiltration difficultly. Given that the frozen ground has
13 extremely low permeability, the surface flow is preferred during the snow melting
14 period (Dunne and Black, 1971).~~The ground with extremely low permeability~~
15 ~~promotes overall surface flow (Dunne and Black, 1971).~~ Or, the melting snowfall
16 accumulates to form a basal saturated zone through which water drains to the stream
17 (Anderson, 1976). Therefore, it is acceptable to assume that melting snow water flow
18 away through channels without evaporation loss. As a consequence, the “effective
19 available water” for evapotranspiration is annual rainfall $(1 - r_s) \cdot P$, rather than total
20 precipitation P .

1 The water-energy balance in form of Eq. (7) with consideration of snow can be
 2 rewritten as follows:

$$\frac{P-Q}{(1-r_s) \cdot P} = [1 + (\frac{E_p}{(1-r_s) \cdot P} - \frac{0.14r_s}{1-r_s})^{-n'}]^{-1/n'} \quad (10)$$

3 Normally, the snow ratio r_s is order of 0.1, with a median value of 0.03 among
 4 studied catchments in Fig. 1 (median value of 0.09 in MOPEX data set used by
 5 Berghuijs et al., 2014). The energy correction term $0.14r_s / (1-r_s)$ in Eq. (10) is
 6 about order of 0.01, and can be neglected compared with the revised dryness index
 7 $E_p / [(1-r_s) \cdot P]$ which is order of 1. Therefore, with little loss of accuracy, the
 8 simplified Eq. (10) can be written as:

$$1 - \frac{Q}{P} = [(1-r_s)^{-n'} + (\frac{E_p}{P})^{-n'}]^{-1/n'} \quad (11)$$

9 3.2 Attribution of runoff change

10 Given the inclusion of snow ratio, Eq. (11) can be used to analyze long-term water
 11 balance of catchment where snow plays a considerable role in hydrological process.
 12 Furthermore, this will provide a theoretical tool to attribute the mean annual runoff
 13 change to climate variability, especially the snow ratio change, and land use/cover
 14 change. An additional assumption that the runoff change is from one steady state to
 15 another one without any transient changes is introduced here. We reorganize Eq. (11)
 16 and differentiate it to calculate change in Q due to changes in climate factors (P , E_p , r_s)
 17 and catchment characteristic (n').

$$Q = P - [P^{-n'} (1-r_s)^{-n'} + E_p^{-n'}]^{-1/n'} \quad (12)$$

18 To first order,

$$dQ = \frac{\partial Q}{\partial P} dP + \frac{\partial Q}{\partial E_p} dE_p + \frac{\partial Q}{\partial r_s} dr_s + \frac{\partial Q}{\partial n'} dn' \quad (13)$$

1 where,

$$\frac{\partial Q}{\partial P} = 1 - \frac{P-Q}{P} \frac{E_p^{n'}}{[P(1-r_s)]^{n'} + E_p^{n'}} \quad (14a)$$

$$\frac{\partial Q}{\partial E_p} = -\frac{P-Q}{E_p} \frac{[P(1-r_s)]^{n'}}{[P(1-r_s)]^{n'} + E_p^{n'}} \quad (14b)$$

$$\frac{\partial Q}{\partial r_s} = \frac{P-Q}{1-r_s} \frac{E_p^{n'}}{[P(1-r_s)]^{n'} + E_p^{n'}} \quad (14c)$$

$$\frac{\partial Q}{\partial n'} = -\frac{P-Q}{n'} \left(\frac{\ln[(P^{n'}(1-r_s)^{n'} + E_p^{n'})]}{n'} - \frac{[P(1-r_s)]^{n'} \ln[P(1-r_s)] + E_p^{n'} \ln(E_p)}{[P(1-r_s)]^{n'} + E_p^{n'}} \right) \quad (14d)$$

2 With Eq. (13), we can estimate the change in runoff between pre- and post-period
 3 due to variations of precipitation, potential evapotranspiration, snow ratio and
 4 catchment parameter, respectively. Specifically, relative contribution of snow ratio
 5 variation to annual runoff change, η_{r_s} , is defined as:

$$\eta_{r_s} = \frac{\Delta Q_{r_s}}{\Delta Q} \cdot \frac{|\Delta Q|}{Q_1} = \text{sgn}(\Delta Q) \cdot \frac{\frac{\partial Q}{\partial r_s} \Delta r_s}{Q_1} \quad (15)$$

6 in which, $\Delta Q_{r_s} = \frac{\partial Q}{\partial r_s} \Delta r_s$. $\Delta Q = Q_2 - Q_1$ and $\Delta r_s = r_{s2} - r_{s1}$ represent difference
 7 between post- and pre-period recorded mean annual runoff and snow ratio,
 8 respectively. $\Delta n'$ represents change in land cover and can be calculated using the
 9 mean annual P and E_p , as well as r_s for each sub-period by Eq. (11).

1 **4 Results and Discussion**

2 **4.1 Effect of snow ratio on runoff**

3 Mean annual runoff index (Q/P) of the 282 catchments are plotted in Fig.2 as a
4 function of dryness index (E_p/P). Each point represents mean annual record for one
5 basin with different color indicating the various snow ratios. The dashed lines are
6 derived from Eq. (7) with different specific catchment parameter, by neglecting
7 changes in catchment storage at the mean annual scale. ~~On the whole, the observed~~
8 ~~data is consistent with the curve pattern, while various catchment properties are~~
9 ~~responsible for the large spread points. Furthermore, t~~There is a general pattern that
10 the catchments with larger snow ratio have higher runoff index for a given dryness
11 index, which is consistent with the findings from datasets in the United States
12 (Berghuijs et al., 2014). However, it is still not sure that the different snow ratio of
13 each catchment results in this kind of variance in runoff index. Before we can make
14 this conclusion, effects of other factors on runoff index need to be excluded.

15 Due to limitation of available catchment data, as well as recent studies implying
16 that the vegetation coverage (Donohue et al., 2007; Voepel et al., 2011; Xu et al., 2013)
17 and average slope (Yang et al., 2009; Yang et al., 2014a) of catchment may be the key
18 control on long-term hydrological partitioning of precipitation, we assume that
19 vegetation coverage and average slope can be thought as two integrators of catchment
20 properties. We estimated the specific catchment parameter n in Eq. (7) from historical
21 observations for each catchment. In order to clear away the impacts that catchment

1 local characteristics (herein the vegetation cover and slope are thought as the proxy of
2 integral characteristics) have on runoff, all catchments are divided into four groups,
3 and catchments in the same group share the similar vegetation coverage or slope.
4 Pearson's linear correlation between specific catchment parameter n and snow ratio in
5 the same group is calculated, by which we can tell whether snow ratio still has
6 significant impact on catchment water-energy balance after getting rid of influence of
7 local catchment properties. Figure 3 and 4 show how specific catchment parameters
8 vary with different snow ratios in each group with similar catchment vegetation cover
9 and average slope, respectively. The results suggest that for those catchments with
10 similar local catchment properties, catchment with higher snow ratio tend to have a
11 smaller specific catchment parameter n . Moreover, the notable negative correlation
12 between catchment parameter n and snow ratio can be seen in the catchments under
13 small and medium vegetation cover (Fig. 3a-c), or large average slope (Fig. 4d).

14 In other words, when excluding the effects of local catchment characteristics,
15 catchments with larger snow ratio are believed to yield more runoff under the same
16 climatological condition. With the above analysis, we can make a more solid
17 conclusion that snow ratio itself indeed has impact on mean annual runoff in the
18 context of [the](#) Budyko hypothesis. Changes in the state of precipitation from snow to
19 rainfall not only affect the seasonal runoff dynamics, but also alter the mean annual
20 runoff amount. Accordingly, how to evaluate the effects of snow ratio on annual
21 runoff variance is meaningful. [What's more, quantifying the sensitivity of annual](#)

1 ~~runoff to snow ratio using a new approach based on the Budyko hypothesis, instead of~~
2 ~~employing least squares estimators of historical records (Berghuijs et al., 2014), may~~
3 ~~provide more insight into this phenomenon. What's more, quantifying the sensitivity~~
4 ~~of annual runoff to snow ratio by assuming linear correlation between these two~~
5 ~~variables and approximating derivatives using least squares estimators of historical~~
6 ~~records (Berghuijs et al., 2014) is not convincing.~~ Therefore, much more elaboration
7 with physic mechanism, like proposed in Sect 3.1, is needed to build.

8 **4.2 Validity of the Budyko framework considering snow effects**

9 We estimated the catchment parameter n' in Eq. (11), and then evaluated the
10 method's validity by investigating the relationship between n' and snow ratio. As
11 shown in Table 2, the correlation between n' value and snow ratio for each catchment
12 was calculated. The correlation approximates to zero and is insignificant, when taking
13 all 282 catchments as a whole. Furthermore, when catchments are grouped by
14 vegetation coverage as Sect 4.1, ~~there is~~ no significant negative correlation is detected,
15 except for group with vegetation coverage of 0.4 - 0.5, and the findings are similar for
16 catchment groups classified by slope.

17 Actually, we intend to analyze the long-term water balance of catchment where
18 snow plays a considerable role in hydrological process. Thus, it may be better to
19 investigate the validity of proposed method by excluding the results from where there
20 is little snow. Afterwards, we further calculate the corresponding correlation for
21 catchments with snow ratio larger than 0.01 and 0.02. Among these catchments, a

1 more significant negative correlation between n estimated by Eq. (7) and snow ratio
2 can be seen, and the correlation coefficients are generally larger in catchments with
3 snow ratio of 0.02, implying the obvious effect of snow ratio on runoff there. Overall,
4 the correlations between n' estimated by Eq. (11) and snow ratio tend to be
5 insignificant. It therefore indicates that ~~the~~Eq. (11) has a good performance for
6 evaluating the impact of snow ratio on mean annual runoff.

7 **4.3 Contribution of climate and land use change to runoff**

8 The annual runoff experiences a downward (decreasing) step change across China
9 around 1980 (Zhang et al., 2008). The change in mean annual runoff is calculated as
10 the difference between ~~post~~period of 1980-2005 and ~~pre~~period of 1956-1979. As
11 shown in Fig.5, most of the study catchments show decreasing runoff change rate,
12 defined as the ratio of runoff change between two periods to mean annual runoff. ~~And~~
13 ~~the relative contributions of four above mentioned factors to change in runoff are~~
14 ~~obtained by taking the derivative of Q with respect to corresponding variables. The~~
15 ~~modeled runoff change is calculated by Eq (13).~~ Figure 6 shows the comparison
16 between modeled runoff changes and the observed for all 282 catchments. The points
17 scatter overall along with the 1:1 line, indicating the proposed attribution method has
18 a good performance for most catchments and it is convincing to analyze the relative
19 contribution of each variable to mean annual runoff variation using this method.

20 The relative contributions of four factors variation to the annual runoff change are
21 depicted in Fig. 7. During the past 50 years, total precipitation amount across China

1 has no obvious trend, while increasing winter precipitation is seen in parts of the
2 northern high latitude and mountains (Sun et al., 2010; Zhang and Cong, 2014). As a
3 result, it is obvious that significant effect of change in snow ratio on annual runoff
4 alteration is found in northwest~~ern~~ mountainous and high-latitude catchments (Fig. 7a)
5 where larger portion of winter precipitation falls in solid state. Generally, the
6 increasing snow ratio makes a negative contribution to the observed decreasing mean
7 annual runoff. And, there is no general spatial pattern where change in total
8 precipitation has a remarkable contribution to annual runoff alteration (Fig. 7b).
9 During the past three decades, northern China, especially ~~Northeast and the~~ North
10 China Plain (Liu et al., 2003), had been seeing significant land use and land cover
11 change, including urbanization and afforestation. And so, a large difference of
12 catchment property n between two studied periods is expected. Among the four
13 variables, the catchment parameter (Fig. 7c) has most significant effects on mean
14 annual runoff change. In most parts of China, the annual E_p shows a decreasing
15 trend, but the decreasing magnitude between post- and pre-period is negligible (Gao et
16 al., 2006). As expected, the overall small negative (<15%) or tiny relative contribution
17 of decreasing E_p to decreasing mean annual runoff is shown in Fig. 7d.

18 **4.4 Plausible future runoff changes**

19 As far as we are concerned, in a plausible future warming climate, quantifying the
20 change in annual runoff resulting from per unit variation in the fraction of
21 precipitation falling as snow is particularly vital for water resources planning. An

1 insight into possible influence of future changing climate, especially snow ratio on
2 annual runoff, is provided here. The 2050-2099 average annual precipitation, snow
3 ratio and E_p of each catchment estimated from the multi-model ensemble averaged
4 values are used as climate forcing to calculate corresponding catchment's future mean
5 annual runoff by Eq. (11), assuming unchanged catchment parameter n' estimated
6 from the past-decade observed data.

7 The projected mean annual runoff increase for 2050-2099 relative to 1956-2005 is
8 widespread in northern China (Fig.8). On the other hand, a slight decrease is projected
9 in most regions of southern China. The spatial pattern of the projected runoff change
10 is consistent with runoff outputs from atmosphere-ocean general circulation models
11 participating in the CMIP5 (Koirala et al., 2014). Mean annual runoff is projected to
12 increase over most of China compared with the 1956-2005 average observation
13 (Fig.8). This The runoff increase projection in parts of northern China mainly results

14 from future increasing precipitation amount, as well as the increasing snowfall, which
15 is also reported by other climate change impact assessments in East Asia (Immerzeel
16 et al., 2013). As shown in Fig. 9, the contribution of snow ratio to runoff change,
17 defined as the ratio of runoff change due to snow ratio change to the total runoff
18 change, is overall positive and pronounced over the catchments located in northern
19 high-latitude and northwestern mountainous regions. The regions are consistent with
20 areas where catchment runoff is sensitive to snow ratio variation over the past several
21 decades as shown in Fig. 7a. Moreover, the patterns of snow ratio's contribution to

1 runoff for RCP4.5 and RCP8.5 scenarios bear some overall resemblance, including
 2 the sensitive areas and magnitudes. Also, some differences exist where snow ratio
 3 change contributes more to runoff increasing for RCP4.5 than RCP8.5, mainly in
 4 central China. Specifically, the snow ratio's contribution to runoff change for RCP4.5
 5 is overall larger than that for RCP8.5, although the differences are insignificant
 6 (Fig.10). This pattern also accords with the projected runoff change relative to the
 7 historical observations (not shown here). It indicates that simulated climate outputs
 8 forced with a midrange mitigation emissions scenario (RCP4.5) tend to more runoff
 9 and larger snow ratio's contribution to runoff change in China, compared with that
 10 under a high emissions scenario.

11 **4.5 Error analysis of attribution method**

12 Since only the first-order approximation of runoff change is used to calculate the
 13 contribution of each variable in the attribution method Eq. (13), we conduct the error
 14 analysis to access its performance in the following. Similar with Yang et al. (2014a),
 15 the Taylor series of Eq. (12) is employed to show the complete expression of runoff
 16 change as:

$$\begin{aligned}
 & Q(P_1 + \Delta P_1, E_{p1} + \Delta E_{p1}, r_{s1} + \Delta r_{s1}, n_1 + \Delta n_1) \\
 & = Q(P_1, E_{p1}, r_{s1}, n_1) \\
 & + (\Delta P_1 \frac{\partial}{\partial P_1} + \Delta E_{p1} \frac{\partial}{\partial E_{p1}} + \Delta r_{s1} \frac{\partial}{\partial r_{s1}} + \Delta n_1 \frac{\partial}{\partial n_1}) Q(P_1, E_{p1}, r_{s1}, n_1) \\
 & + \frac{1}{2!} (\Delta P_1 \frac{\partial}{\partial P_1} + \Delta E_{p1} \frac{\partial}{\partial E_{p1}} + \Delta r_{s1} \frac{\partial}{\partial r_{s1}} + \Delta n_1 \frac{\partial}{\partial n_1})^2 Q(P_1, E_{p1}, r_{s1}, n_1) + \dots
 \end{aligned} \tag{16}$$

17 The runoff change induced by the snow ratio change can be expressed as:

$$\Delta Q_{\Delta r_s} = \Delta r_{s1} \frac{\partial}{\partial r_{s1}} Q(P_1, E_{p1}, r_{s1}, n_1) + \frac{1}{2!} (\Delta r_{s1} \frac{\partial}{\partial r_{s1}} + \Delta P_1 \frac{\partial}{\partial P_1} + \Delta E_{p1} \frac{\partial}{\partial E_{p1}} + \Delta n_1 \frac{\partial}{\partial n_1}) \Delta r_{s1} \frac{\partial}{\partial r_{s1}} Q(P_1, E_{p1}, r_{s1}, n_1) \quad (17)$$

1 in which, we neglect the third- and higher-order terms of Eq. (16) for the third-order is
 2 equal to 3% of the second-order according to Yang et al. (2014b). The relative error
 3 (RE) of attribution method to investigate the contribution of snow ratio change is
 4 estimated as:

$$RE_{\Delta r_s} = \left| \frac{\Delta Q_{\Delta r_s} - \Delta Q_{r_s}}{\Delta Q_{\Delta r_s}} \right| \quad (18)$$

5 As shown in Fig.11, the relative errors of attribution method with respect to snow
 6 ratio change are small for all 282 catchments. Specifically, as for the contribution of
 7 snow ratio change to the historical runoff, the RE of more than 90% catchments is no
 8 more than 11%. As to the two projected future climate change scenarios, the REs of
 9 more than 90% catchments are less than 8% and 12% for RCP4.5 and RCP 8.5,
 10 respectively. Therefore, the proposed first-order approximation attribution method is
 11 reliable.

12 **4.6 limitation of revised Budyko framework**

13 It should be noted that the assumption of no evapotranspiration loss in snowmelt
 14 adopted in Section 3.1 is not universally applicable. In small catchments, after
 15 snowfall is melt and the concrete frozen ground inhibits snowmelt infiltration, the
 16 snow water can flow away quickly through channels without evaporation loss.
 17 However, if the location of accumulated snow is far away from channels, or the
 18 snowfall amount is large, it will take longer for melt water to run off than the frozen

1 soil thaws. In these cases, a part of snow infiltrates into the ground and later is
2 available for evaporation (Dripps, 2012; Jasechko et al., 2014). In fact, it may be more
3 suitable to introduce as “effective available water” for evapotranspiration, where k
4 is a loss parameter requiring further investigation. To better understand and
5 parameterize the snowmelt loss by evapotranspiration, the site-specific modeling and
6 isotope-based field observations may provide tools for more detailed modeling in the
7 future.

8 Apart from limitation of the assumption, the accurate estimation of snow ratio is
9 also important for this framework. However, direct snow observation records are not
10 available for the case study watersheds in this manuscript and the MOPEX watersheds
11 used by Berguijjs et al. (2014). Mean annual snowfall is estimated by the air
12 temperature-based empirical method. The threshold temperature is critical for
13 calculating the snowfall amount. A higher threshold temperature will overestimate the
14 snow ratio that may lead to an unreasonable conclusion under the framework in our
15 study. According to the sensitivity analysis of catchment parameter estimation, it
16 shows that a small variation in snow ratio can lead to a significant change in
17 catchment parameter when snow ratio is large enough to be comparable to runoff
18 index. Thus, the accuracy of snow ratio is important to this framework especially
19 when the snow ratio is large, which limits the applicability of this framework in those
20 catchments.

1 **5 Conclusions**

2 In this study, we showed that snow ratio could have a pronounced effect on mean
3 annual runoff based on both historical records and theoretical analysis. In the context
4 of [the](#) Budyko hypothesis, catchments with larger snow ratio tend to yield more
5 long-term mean annual runoff given the same other climatological and landscape
6 properties. Moreover, a Budyko-type equation considering the water-energy balance is
7 derived to quantify the effects of snow ratio on runoff. With the assistance of
8 proposed relationship, the contribution of snow ratio to change in annual runoff
9 during the past five decades and potential annual runoff variation due to changing
10 fraction of precipitation falling as snow under projected future global warming
11 scenario in China are investigated. The results indicate that those sensitive catchments
12 in [northwestern](#) mountainous and north-central high-latitude areas are undergoing
13 remarkable runoff change resulting from snow ratio variance. In addition, the error
14 analysis of attribution method is conducted, implying that the first-order
15 approximation is suitable to assess the contribution of snow ratio change to runoff in
16 this study.

17 This paper extends the previous work that suggested that precipitation shift from
18 snow towards rain leads to a decrease in runoff based on dataset in U.S. (Berghuijs et
19 al., 2014). We confirm here that the observations in China give a similar conclusion.
20 What's more, we quantify this effect and assess the impact of climate change,
21 especially snow ratio change, on mean annual runoff across China. As major rivers

1 originating from mountainous regions where temperature determinates the state of
2 precipitation (Allamano et al., 2009) and afterwards affects annual runoff amount as
3 discussed above, the findings here have valuable implications for future water
4 management policy. The proposed model can be made applicable to other
5 mountainous catchments of the world easily and quantify the effects of possible
6 change in snow ratio on available water resources and analyze the vulnerability of
7 catchments to climate change.

8

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15

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11

12

Table 1. Overview of selected GCMs used in climate impact assessment. More details of the models, modeling centers and meaning of the ensemble codes can be found at <http://cmip-pcmdi.llnl.gov/cmip5/availability.html>.

| RCP4.5 | | | RCP8.5 | | |
|--------|----------------|----------|--------|----------------|----------|
| NO. | Model | Ensemble | NO. | Model | Ensemble |
| 1 | ACCESS1.0 | r1i1p1 | 1 | ACCESS1.0 | r1i1p1 |
| 2 | ACCESS1.3 | r1i1p1 | 2 | ACCESS1.3 | r1i1p1 |
| 3 | BCC-CSM1-1 | r1i1p1 | 3 | BCC-CSM1-1 | r1i1p1 |
| 4 | BCC-CSM1-1-m | r1i1p1 | 4 | BCC-CSM1-1-m | r1i1p1 |
| 5 | BNU-ESM | r1i1p1 | 5 | BNU-ESM | r1i1p1 |
| 6 | CCSM4 | r1i1p1 | 6 | CANESM2 | r1i1p1 |
| 7 | CESM1-BGC | r1i1p1 | 7 | CCSM4 | r1i1p1 |
| 8 | CESM1-CAM5 | r1i1p1 | 8 | CESM1-BGC | r1i1p1 |
| 9 | CESM1-WACCM | r1i2p1 | 9 | CESM1-CAM5 | r1i1p1 |
| 10 | CMCC-CM | r1i1p1 | 10 | CESM1-WACCM | r1i2p1 |
| 11 | CMCC-CMS | r1i1p1 | 11 | CMCC-CESM | r1i1p1 |
| 12 | CNRM-CM5 | r1i1p1 | 12 | CMCC-CM | r1i1p1 |
| 13 | CSIRO-Mk3-6-0 | r1i1p1 | 13 | CMCC-CMS | r1i1p1 |
| 14 | CANESM2 | r1i1p1 | 14 | CNRM-CM5 | r1i1p1 |
| 15 | EC-EARTH | r5i1p1 | 15 | CSIRO-Mk3-6-0 | r1i1p1 |
| 16 | FGOALS-g2 | r1i1p1 | 16 | EC-EARTH | r2i1p1 |
| 17 | FIO-ESM | r1i1p1 | 17 | FGOALS-g2 | r1i1p1 |
| 18 | GFDL-CM3 | r1i1p1 | 18 | FIO-ESM | r1i1p1 |
| 19 | GFDL-ESM2G | r1i1p1 | 19 | GFDL-CM3 | r1i1p1 |
| 20 | GFDL-ESM2M | r1i1p1 | 20 | GFDL-ESM2G | r1i1p1 |
| 21 | GISS-E2-H | r1i1p1 | 21 | GFDL-ESM2M | r1i1p1 |
| 22 | GISS-E2-H-CC | r1i1p1 | 22 | GISS-E2-H | r1i1p1 |
| 23 | GISS-E2-R | r1i1p1 | 23 | GISS-E2-H-CC | r1i1p1 |
| 24 | GISS-E2-R-CC | r1i1p1 | 24 | GISS-E2-R | r1i1p1 |
| 25 | HadGEM2-CC | r1i1p1 | 25 | GISS-E2-R-CC | r1i1p1 |
| 26 | HadGEM2-ES | r1i1p1 | 26 | HadGEM2-CC | r1i1p1 |
| 27 | INMCM4 | r1i1p1 | 27 | HadGEM2-ES | r1i1p1 |
| 28 | IPSL-CM5A-LR | r1i1p1 | 28 | INMCM4 | r1i1p1 |
| 29 | IPSL-CM5A-MR | r1i1p1 | 29 | IPSL-CM5A-LR | r1i1p1 |
| 30 | IPSL-CM5B-LR | r1i1p1 | 30 | IPSL-CM5A-MR | r1i1p1 |
| 31 | MIROC-ESM | r1i1p1 | 31 | IPSL-CM5B-LR | r1i1p1 |
| 32 | MIROC-ESM-CHEM | r1i1p1 | 32 | MIROC5 | r1i1p1 |
| 33 | MIROC5 | r1i1p1 | 33 | MIROC-ESM | r1i1p1 |
| 34 | MPI-ESM-LR | r1i1p1 | 34 | MIROC-ESM-CHEM | r1i1p1 |
| 35 | MPI-ESM-MR | r1i1p1 | 35 | MPI-ESM-LR | r1i1p1 |
| 36 | MRI-CGCM3 | r1i1p1 | 36 | MPI-ESM-MR | r1i1p1 |
| 37 | NorESM1-M | r1i1p1 | 37 | MRI-CGCM3 | r1i1p1 |

| | | | | | |
|----|------------|--------|----|------------|--------|
| 38 | NorESM1-ME | rli1p1 | 38 | MRI-ESM1 | rli1p1 |
| | | | 39 | NorESM1-M | rli1p1 |
| | | | 40 | NorESM1-ME | rli1p1 |

Table 2. Summary of correlation between specific catchment parameter and snow ratio for different catchment groups. (n is estimated by Eq.(7); n' is estimated by Eq.(11))

| | all 282 catchments | | catchments with $r_s > 0.01$ | | catchments with $r_s > 0.02$ | |
|----------------------------|--------------------|--------|------------------------------|---------|------------------------------|----------|
| | n | n' | n | n' | n | n' |
| As a whole | -0.21*** | 0.05 | -0.27*** | 0.04 | -0.38*** | -0.03 |
| Vegetation Coverage | | | | | | |
| 0.1 - 0.3 | -0.50*** | -0.03 | -0.50*** | -0.03 | -0.50*** | -0.03 |
| 0.3 - 0.4 | -0.49*** | -0.32* | -0.44*** | -0.28 | -0.48*** | -0.32* |
| 0.4 - 0.5 | -0.44*** | -0.38* | -0.47*** | -0.36** | -0.59*** | -0.48*** |
| 0.5 - 0.7 | -0.09 | 0.18 | 0.03 | 0.08 | -0.04 | 0 |
| Slope (%) | | | | | | |
| 0.2 - 3.8 | -0.24* | 0.01 | -0.25* | -0.03 | -0.30** | -0.07 |
| 3.8 - 5.5 | -0.14 | 0.27 | -0.06 | 0.33 | -0.16 | 0.26 |
| 5.5 - 8.0 | -0.20 | -0.03 | -0.35*** | -0.14 | -0.41*** | -0.19 |
| 8.0 - 18.7 | -0.40*** | -0.29* | -0.47*** | -0.36** | -0.45*** | -0.34* |

Note: *, ** and *** indicate the significant level at 0.05, 0.01 and 0.001, respectively.

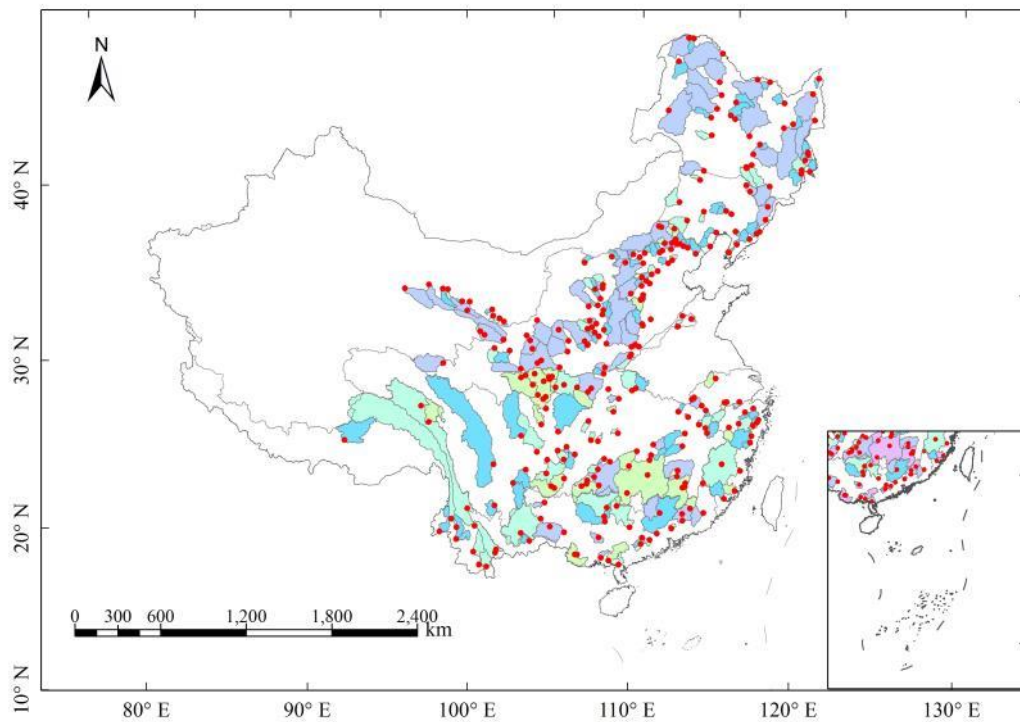
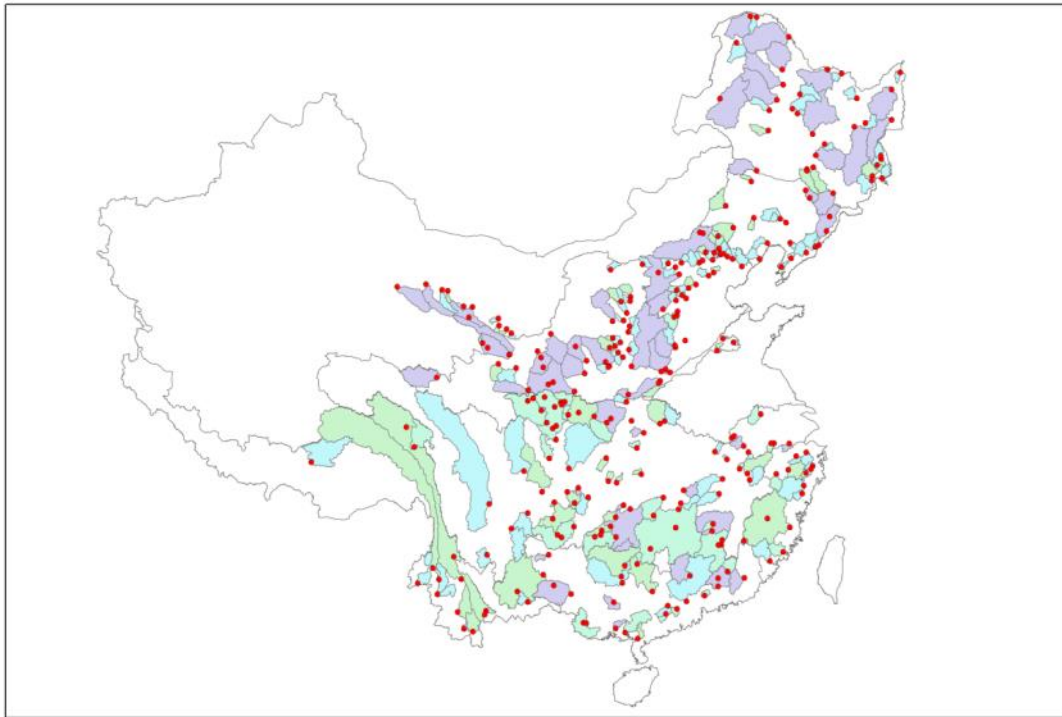


Fig.1 The location of the study catchments. Red points represent catchment runoff gauge stations.

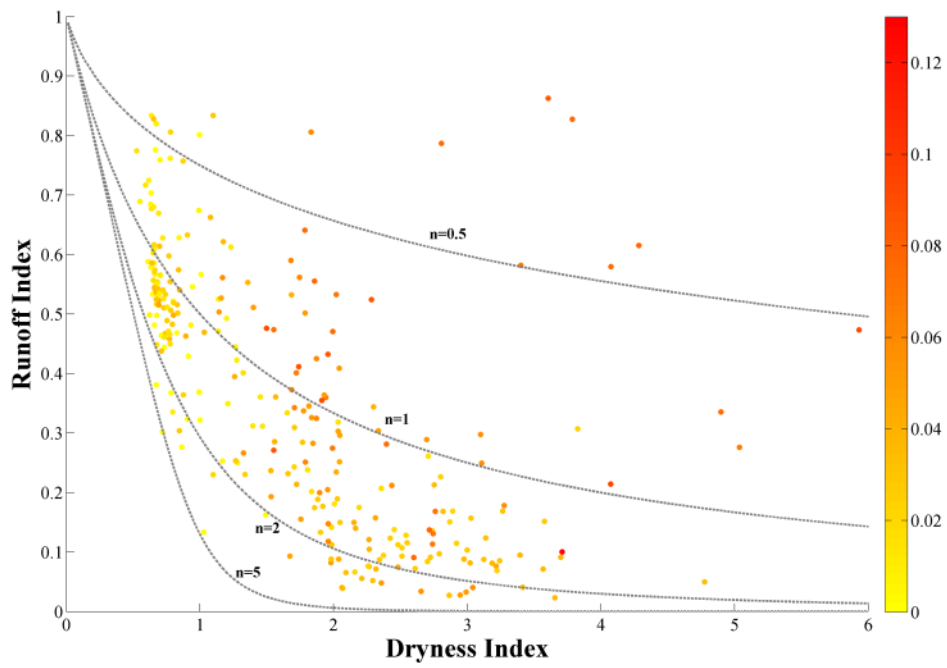


Fig.2 The 282 long-term climatological water budget observations in China. Each point represents a catchment. The color refers to snow ratio. Dashed lines are derived from Eq.(7) with different n values.

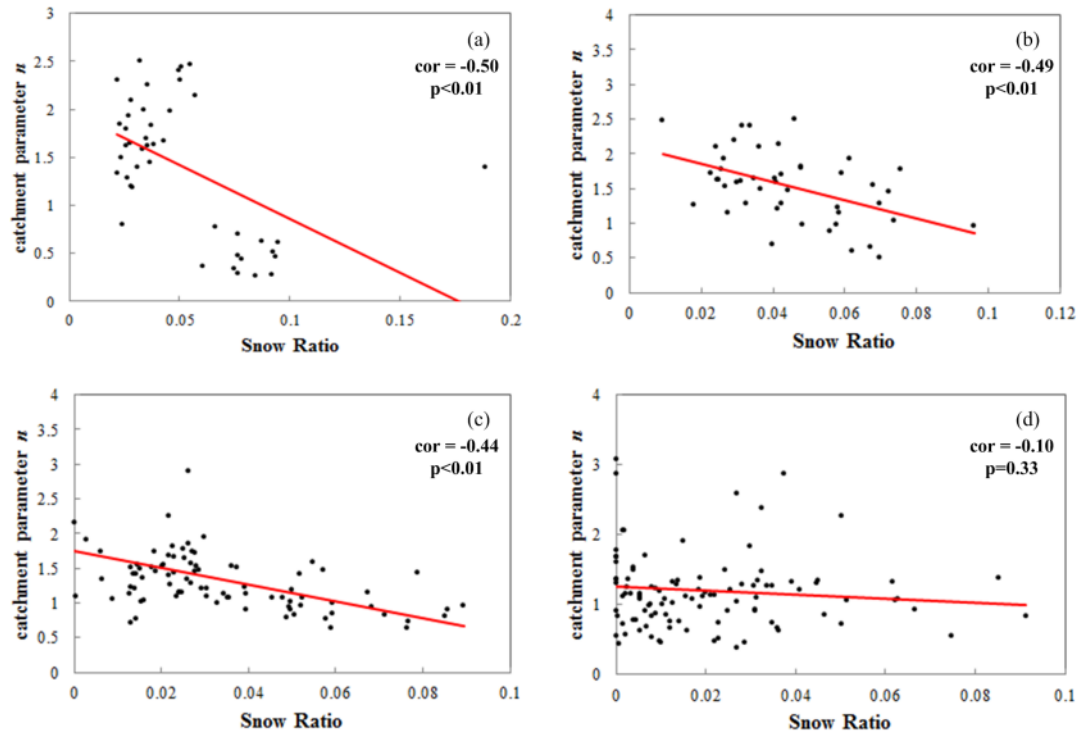


Fig.3 In the context of the Budyko-Choudhury framework, statistical relationships between specific catchment parameter n and snow ratio, under similar vegetation coverage. Least squares regression lines are shown on each of the plots. The small Pearson's linear correlation coefficient clarifies the significant negative correlation between snow ratio and catchment parameter. (a) - (d) indicate the vegetation coverage of < 0.3 , $(0.3, 0.4)$, $(0.4, 0.5)$, and > 0.5 , respectively. ~~(a) - (d) indicate the vegetation coverage of < 0.3 , $[0.3, 0.4]$, $(0.4, 0.5)$, and > 0.5 , respectively.~~

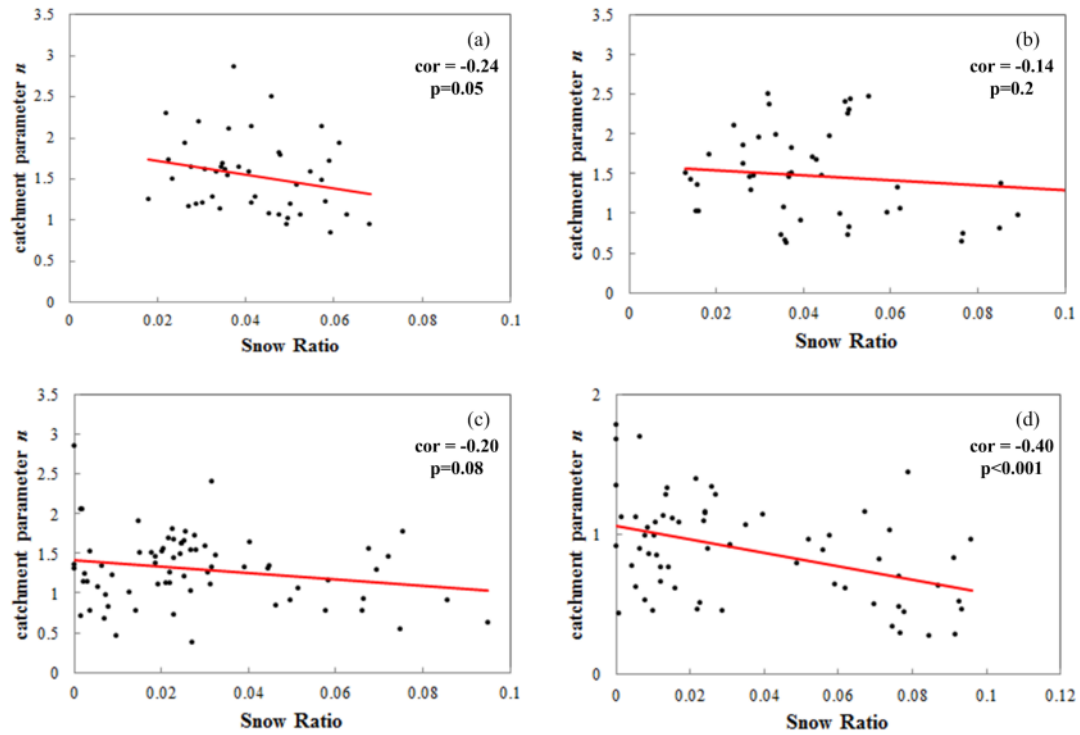


Fig.4 Similar with Fig.3 for catchment average slope. (a) - (d) indicate the average slope (%) of (0.2 3.8), (3.8 5.5), (5.5 8.0), and > 8.0, respectively.
~~Fig.4 Similar with Fig.3 for catchment average slope. (a) - (d) indicate the average slope (%) of [0.2 3.8], (3.8 5.5], (5.5 8.0], and (8.0 18.7], respectively.~~

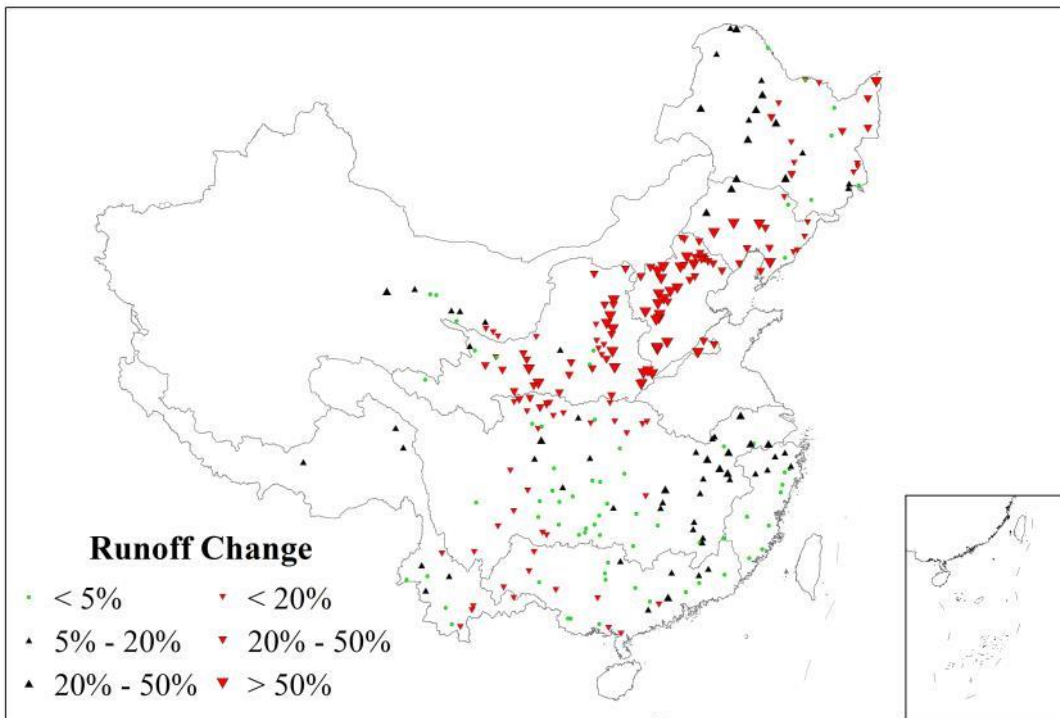
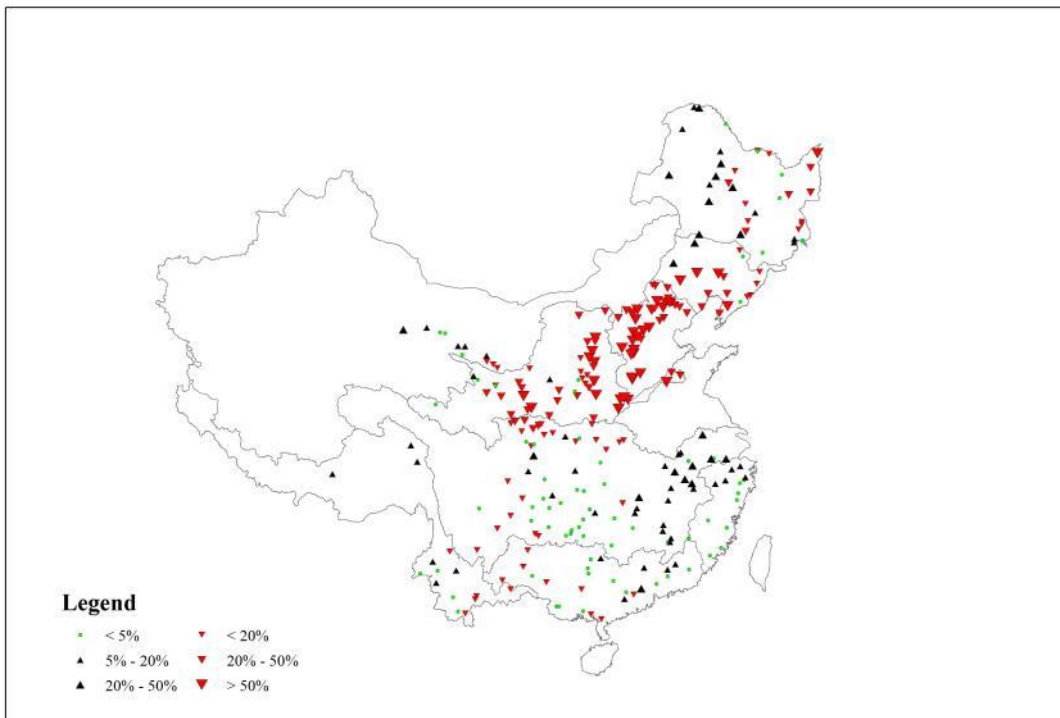


Fig.5 Mean annual runoff change rate between two periodspost – and pre – period.

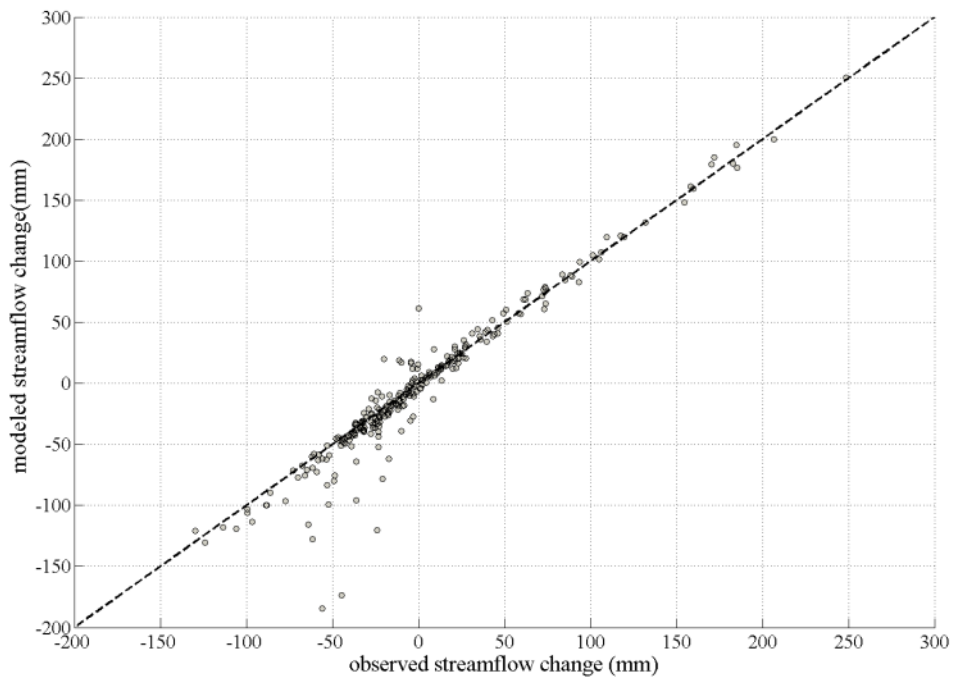
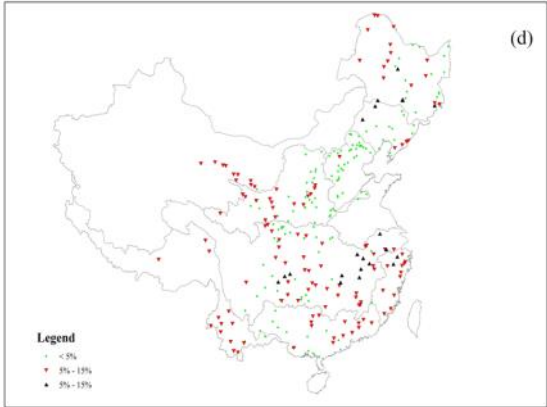
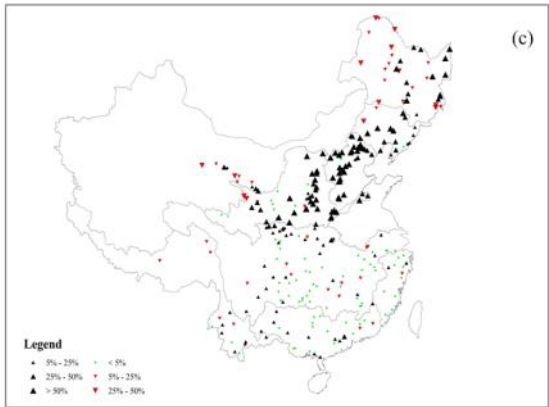
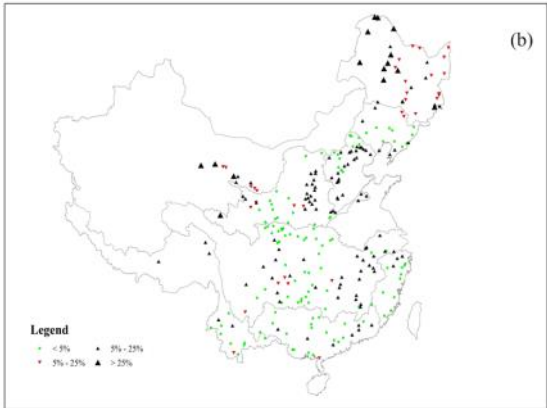
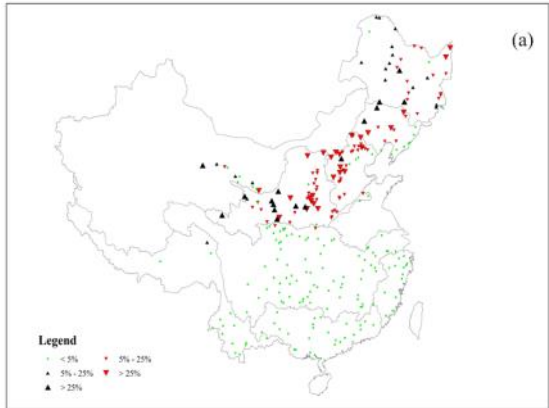


Fig.6 Comparison between observed and calculated mean annual runoff change.



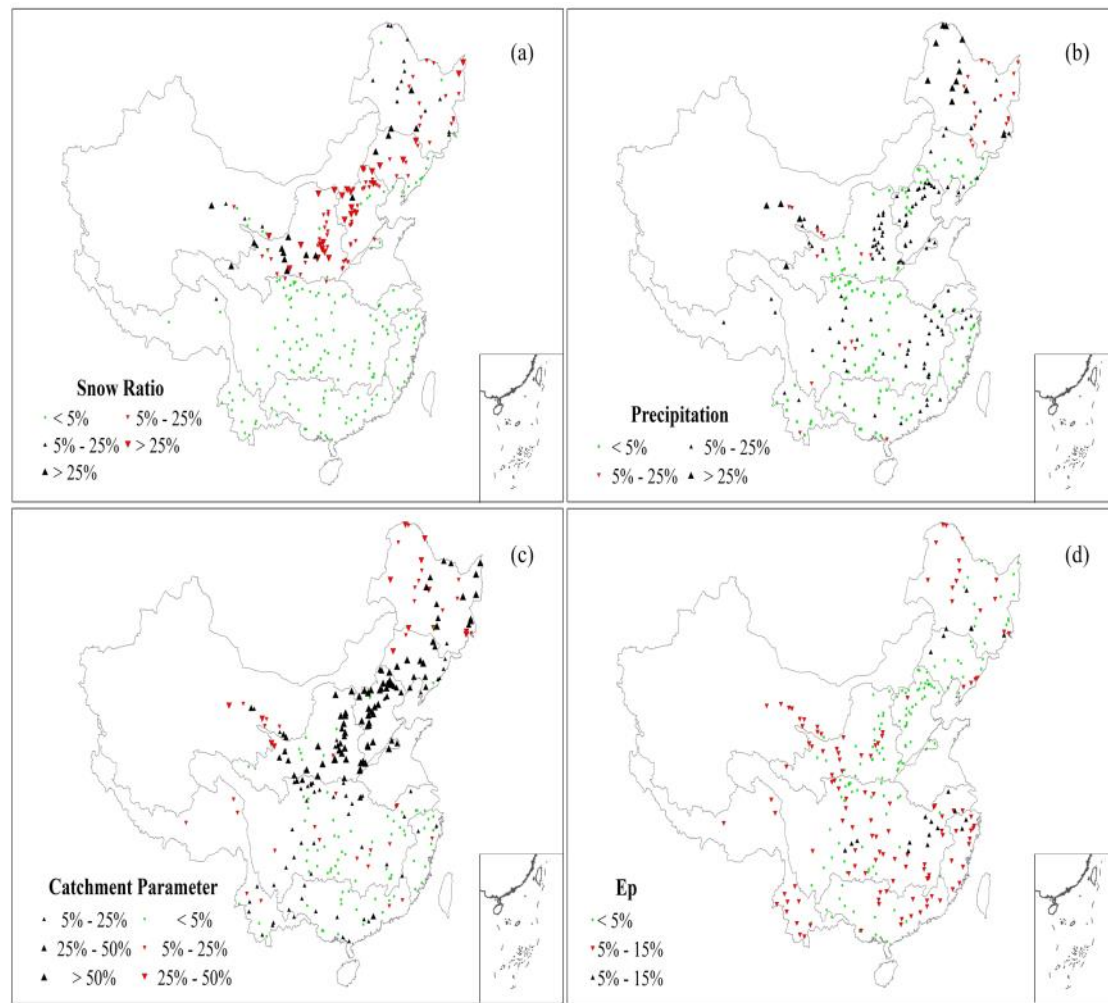
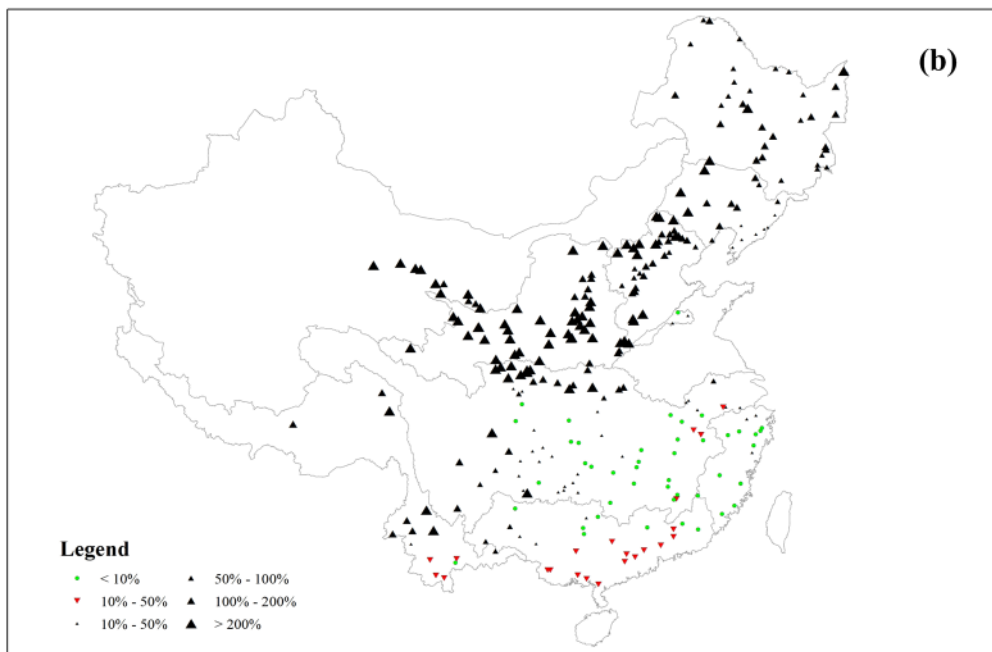
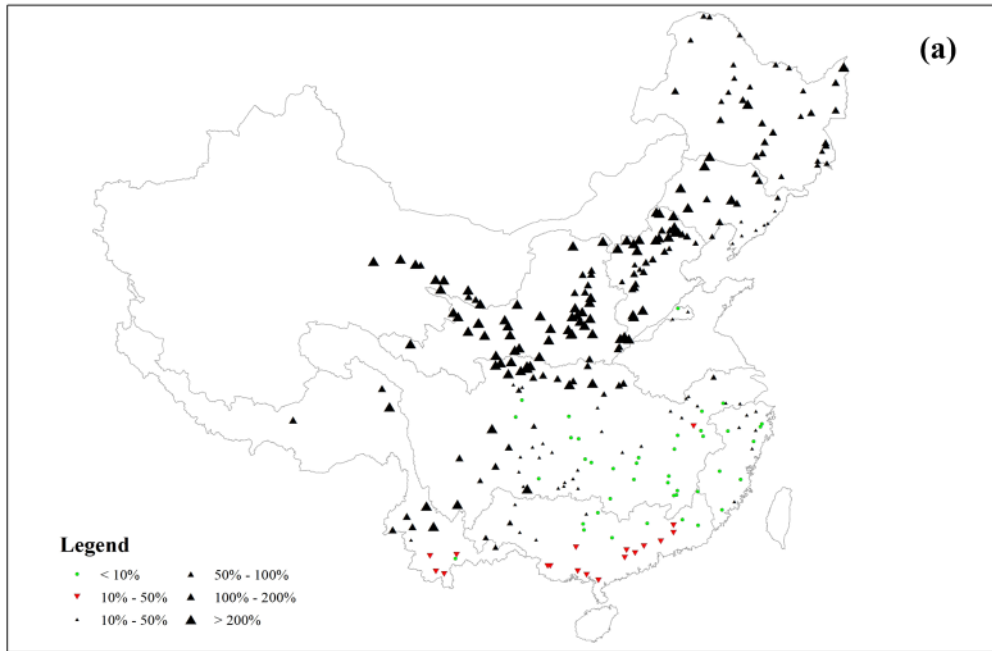


Fig.7 Relative contributions of (a) snow ratio, (b) precipitation, (c) specific catchment parameter, and (d) potential evapotranspiration variance to change in mean annual runoff. Upward triangle represents the positive relative contribution of the variable to change in runoff; downward triangle represents the negative.



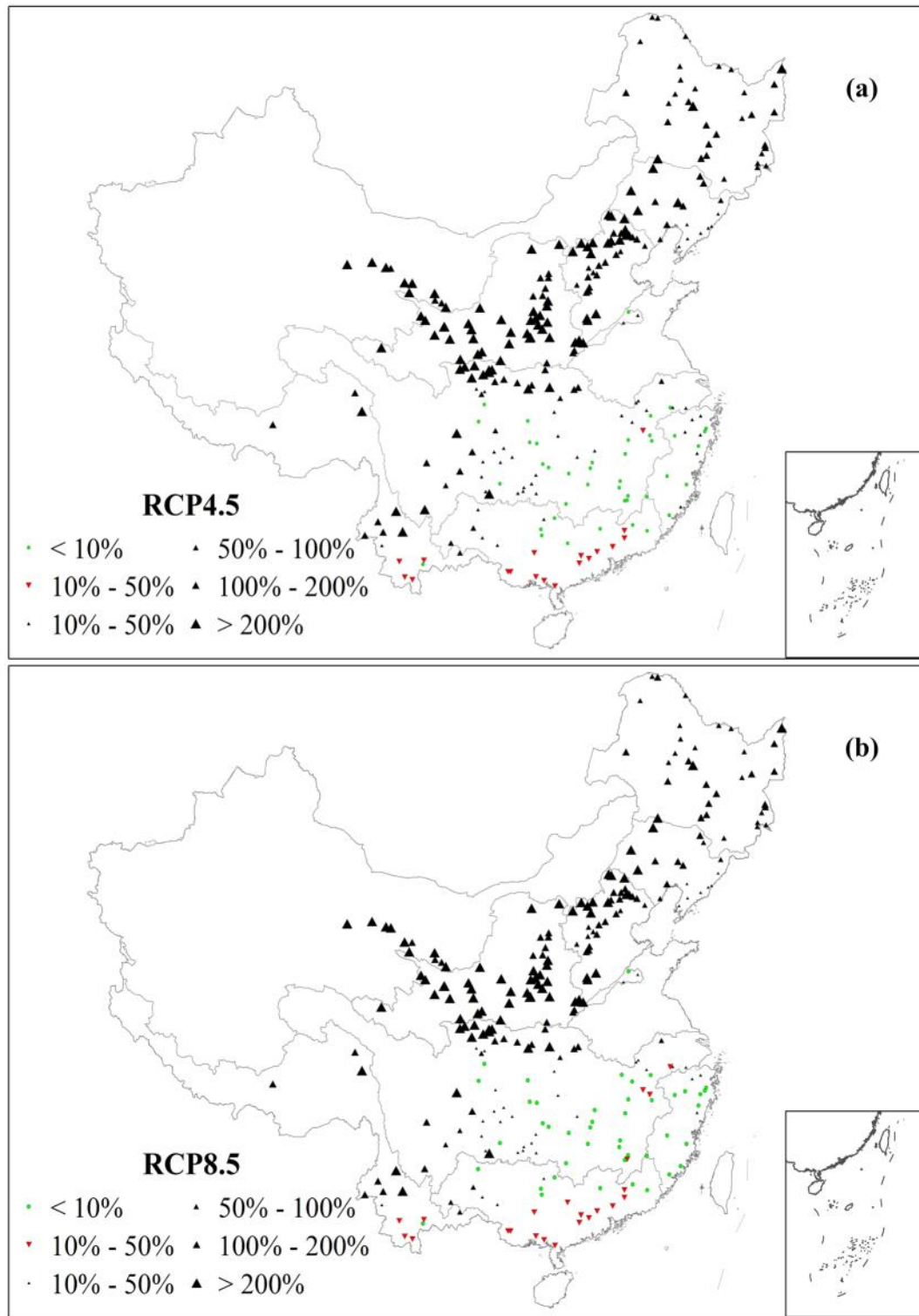
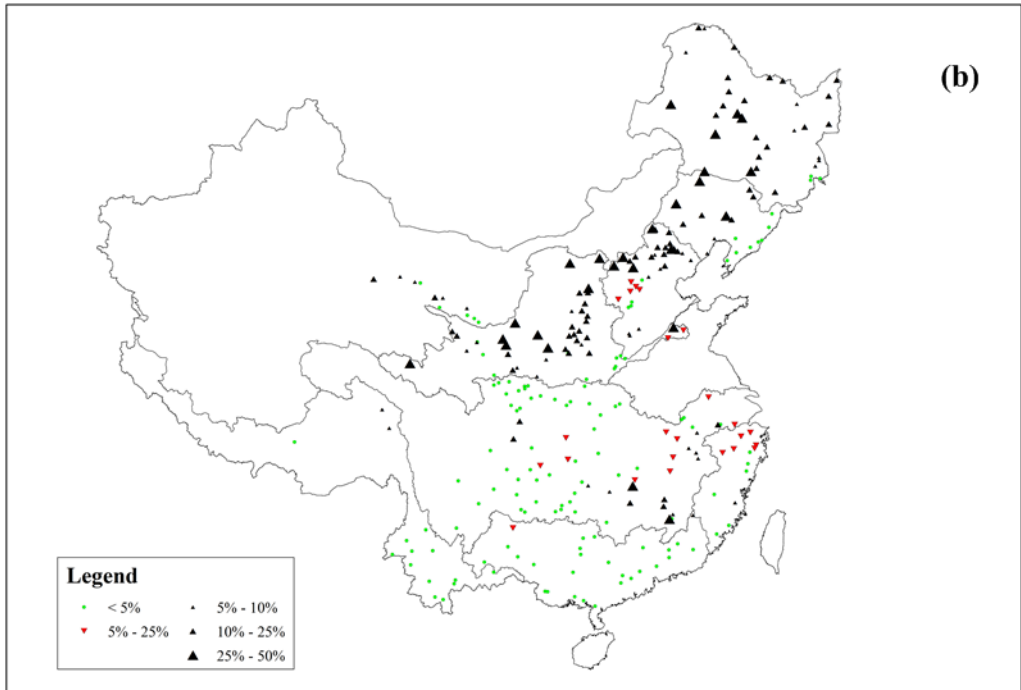
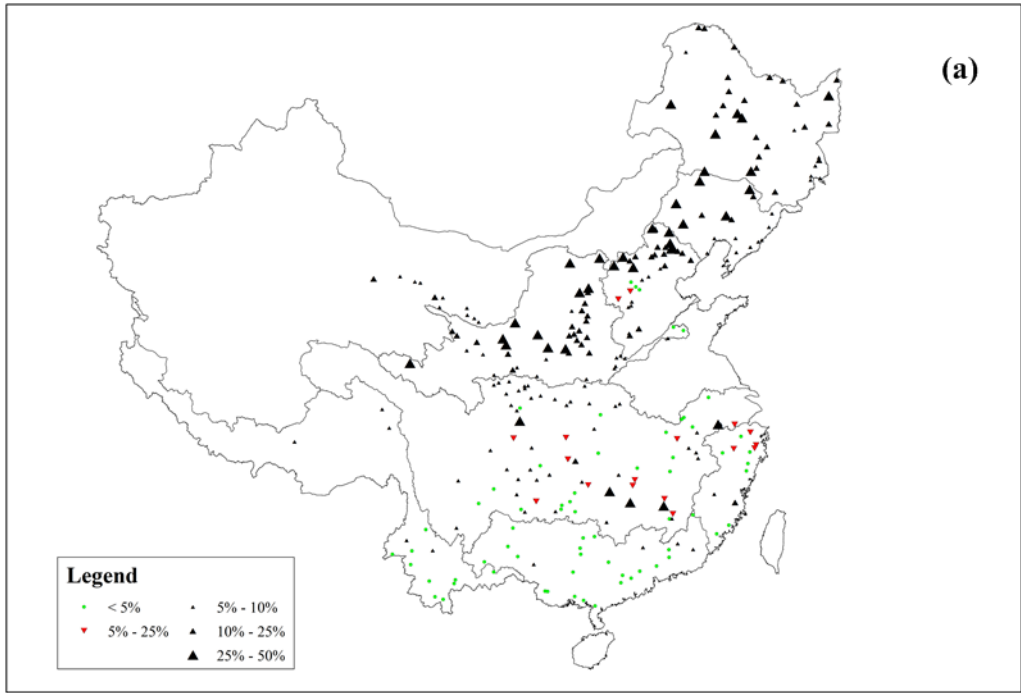


Fig. 8 Change rate of mean annual runoff under projected future climate. (a: RCP4.5; b: RCP8.5).



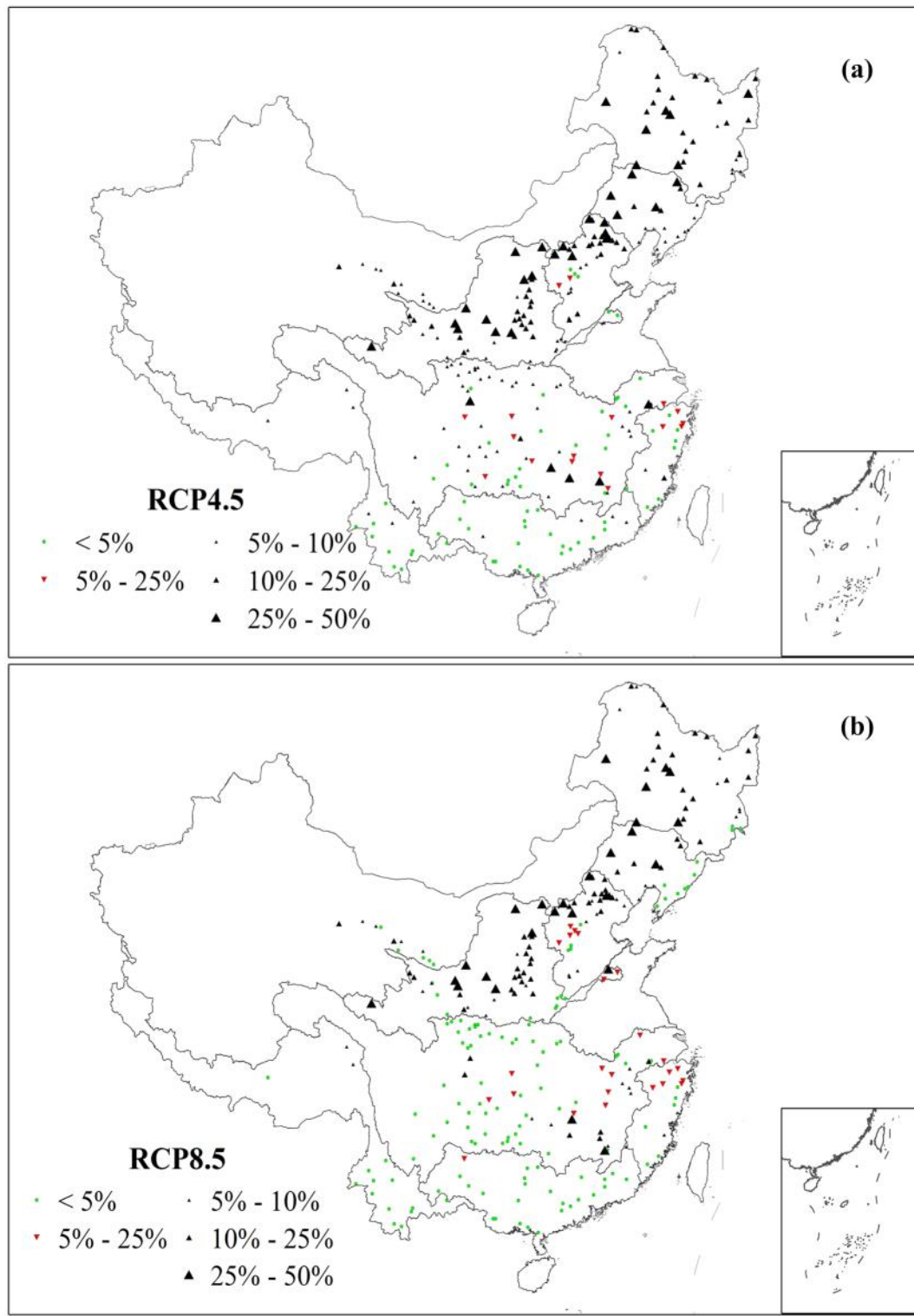


Fig.9 Contribution of snow ratio variance to change in mean annual runoff under projected future climate. (a: RCP4.5; b: RCP8.5).

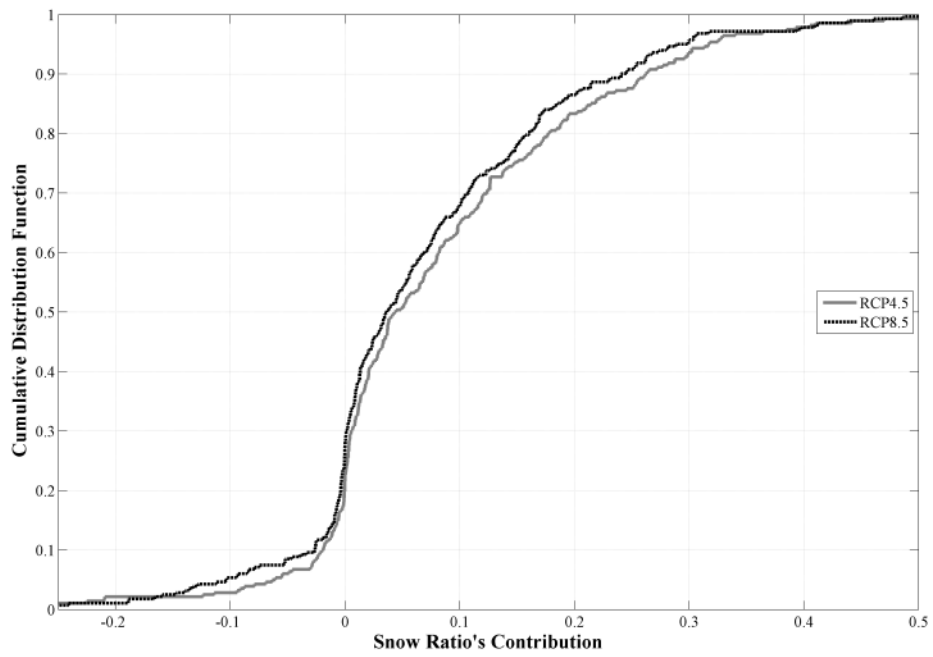


Fig.10 Cumulative distribution function of snow ratio's contribution to runoff change under projected future climate.

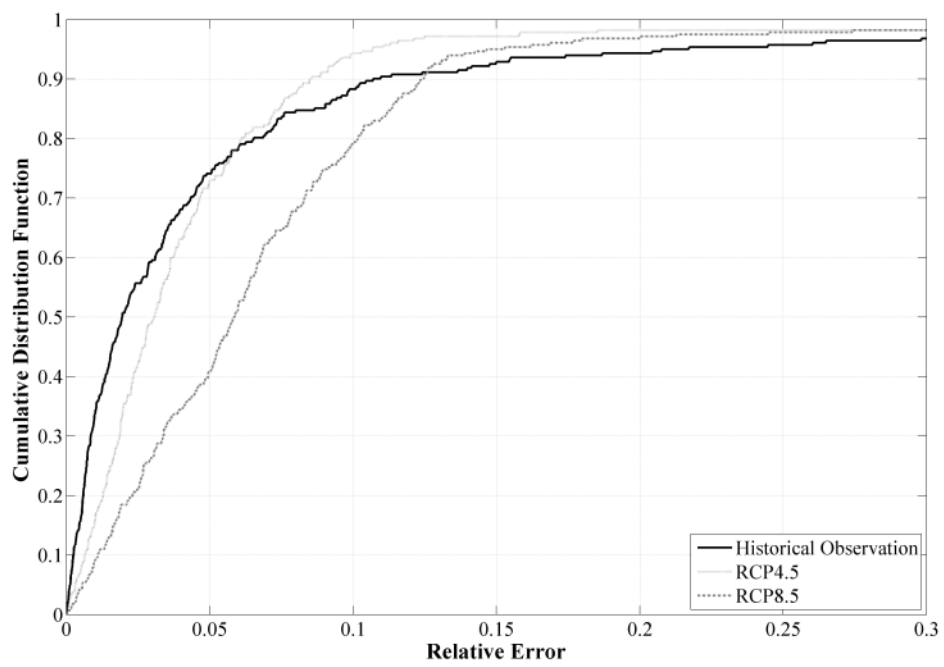


Fig.11 Cumulative distribution function of the relative error of attribution method in three cases.