

# Geophysical Research Letters

## RESEARCH LETTER

10.1029/2018GL078646

### Key Points:

- Response of runoff to global warming varies across warming levels and river basins
- Runoff in many subtropical river basins exhibits evident nonlinear response to warming
- Runoff response could change substantially when global temperature rises beyond 1.5°C

### Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2

### Correspondence to:

Q. Tang,  
tangqh@igsnr.ac.cn

### Citation:

Zhang, X., Tang, Q., Liu, X., Leng, G., & Di, C. (2018). Nonlinearity of runoff response to global mean temperature change over major global river basins. *Geophysical Research Letters*, 45, 6109–6116. <https://doi.org/10.1029/2018GL078646>

Received 6 MAY 2018

Accepted 30 MAY 2018

Accepted article online 8 JUN 2018

Published online 28 JUN 2018

## Nonlinearity of Runoff Response to Global Mean Temperature Change Over Major Global River Basins

Xuejun Zhang<sup>1</sup> , Qihong Tang<sup>1,2</sup> , Xingcai Liu<sup>1</sup> , Guoyong Leng<sup>3</sup> , and Chongli Di<sup>4</sup>

<sup>1</sup>Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China, <sup>2</sup>University of Chinese Academy of Sciences, Beijing, China, <sup>3</sup>Environmental Change Institute, University of Oxford, Oxford, UK, <sup>4</sup>Institute of Surface-Earth System Science, Tianjin University, Tianjin, China

**Abstract** We investigated the nonlinearity of runoff response to global mean temperature (GMT) change in the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models at the river basin scale globally. Results show that changes in long-term mean annual runoff are nonlinear with GMT rise over most extended subtropical basins, suggesting that estimation of future runoff change derived from the linear scaling relations would be biased. As for the interannual variability, nonlinearities are apparent mainly in central and western Asia, southern and western Africa, most of Europe, and Australia when GMT increases beyond 1.5°C. This suggests that impacts of climate change under 1.5°C GMT rise on runoff variability should not be simply scaled from that under a 2°C warming world. Our results highlight the contrasting response of areal runoff to GMT rise across global major river basins and reveal the threshold of GMT increment at which the nonlinear runoff response is projected to emerge.

**Plain Language Summary** This paper addresses the nonlinear response of areal runoff to global warming at river basin scale globally and reveals the specific basins and the target global mean temperature rise where and when the nonlinearity is projected to occur. Furthermore, we highlight the possible mechanisms behind the revealed nonlinear response of river basin mean runoff to global mean temperature rise. These findings greatly differ from the global-scale linear relation concluded from previous analyses. This will provide great scientific implications for the ongoing impact assessment of limiting global warming to 1.5° advocated by 2015 Paris agreement, and thus benefit local climate impact assessment, mitigation, and adaptation.

## 1. Introduction

The ongoing climate change has been significantly affecting the terrestrial water cycle (Held & Soden, 2006; Intergovernmental Panel on Climate Change (IPCC), 2014; Tang & Oki, 2016), including river runoff (Milly et al., 2005; Nohara et al., 2006; Tang & Lettenmaier, 2012). Changes in the timing, magnitude, and seasonality of river runoff as a result of global warming would pose huge threats to water security (Schewe et al., 2014), especially over regions that are facing water scarcity or will experience drying. Global mean temperature (GMT) change as an index of cumulative greenhouse gas emissions (Knutti et al., 2016) has been broadly adopted for coordinating mitigation efforts to reduce the negative impacts associated with climate warming (Meinshausen et al., 2009). Therefore, investigating future runoff change in response to GMT rise can provide us valuable insights on the impacts of anthropogenic climate change on water resources.

There have been considerable efforts devoted to assessing the potential hydrological impacts of climate change under a prescribed GMT warming level. Since the 2009 climate conference, limiting global temperature rise to 2°C above preindustrial level has been widely advocated for preventing adverse climate change impacts (United Nations Framework Convention on Climate Change, 2010). Numerous studies have been conducted on future changes in river runoff (Singh et al., 2010), water resources availability (Haddeland et al., 2014; Schewe et al., 2014), and hydrological extremes (Roudier et al., 2016) under a 2°C warming world. Recently, the Paris agreement has advocated limiting global warming to below 1.5°C (United Nations Framework Convention on Climate Change, 2015), which promotes quantitative investigations on the impacts of 1.5°C GMT rise (Donnelly et al., 2017; Marx et al., 2017), as well as the comparison with other warming levels (Arnell & Gosling, 2016; Gosling et al., 2017; Leng, Tang, et al., 2016). Based on climate projections archived in the Coupled Model Intercomparison Project Phase 3 (CMIP3), Tang and Lettenmaier (2012)

estimated the percentage change of runoff in response to five GMT increments (0.5, 1, 1.5, 2, and 2.5°C) and found an approximate linear relationship between global mean runoff change and GMT change, independent of emission pathways. Zhang et al. (2014) confirmed this finding based on the state-of-the-art climate projections archived in the CMIP5 and highlighted that changes in future global mean runoff could be simply scaled among various global warming levels. For instance, a 2°C increase in GMT would lead to changes in continental total runoff twice as much as that under a 1°C warming world.

To date, few studies have focused on the linkage between regional runoff change and global warming (Gosling et al., 2017; Yang et al., 2017). Leng, Huang, et al. (2016) investigated the response of subbasin hydrological regime to GMT rise over the conterminous United States (CONUS) using runoff projections by a hydrological model forced with bias-corrected climate data. However, it is still unclear whether the linear response of runoff to GMT rise on the global scale holds at the river basin scale.

In this study, we investigate the response of regional-scale runoff of global major river basins to GMT rise. Specifically, we aim to address the following questions: (1) whether and where runoff magnitude (means) and year-to-year (inter-annual) variability respond nonlinearly to the increment of GMT? (2) At which level of GMT rise the nonlinear response of basin-scale runoff to global warming are expected to emerge? This work will advance our understanding on the response of runoff to different GMT warming levels from a regional perspective, and thus greatly benefit climate impact assessment, regional mitigation, and adaptation.

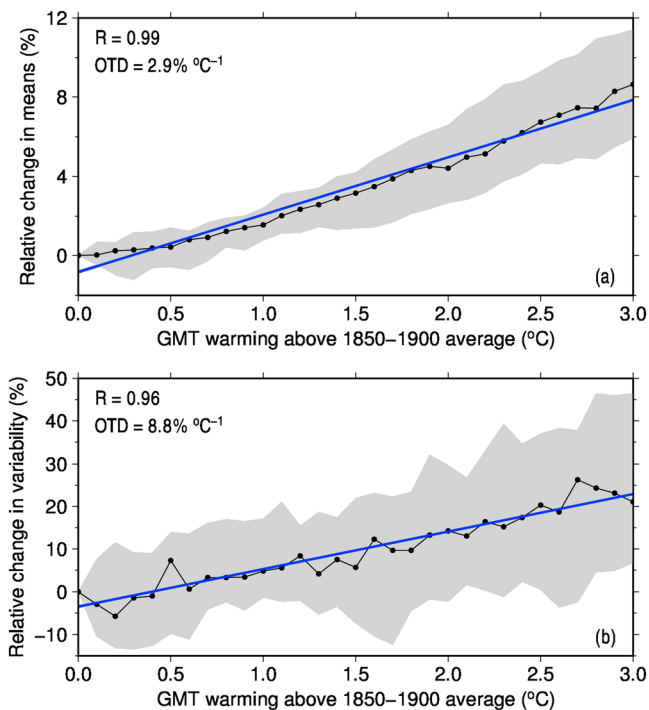
## 2. Data and Methods

In this study, 194 global large river basins were identified from the Simulated Topological Network (STN-30p; Vörösmarty et al., 2000) according to the drainage area, as has been done in Tang and Lettenmaier (2012). We analyzed annual temperature and runoff projections from 34 CMIP5 climate models under four Representative Concentration Pathways (RCPs). For each climate model and each RCP scenario, relative change in the mean and interannual variability of basin-averaged runoff was calculated between the preindustrial era (1850–1900) and each 30-year future period corresponding to a prescribed GMT rise varying from 0.1 to 3°C at an interval of 0.1°C (see Text S1 in the supporting information). Although a recent study reported that multimodel ensemble mean is not always superior to individual models (Zaherpour et al., 2018), we did not try to select specific climate models from the pool of CMIP5 according to their performance. Here the multimodel ensemble medians (MMs) estimated from the subsets formed by the total 34 climate models under 4 RCP scenarios were calculated and used for analysis following previous studies (Mote et al., 2011; Pierce et al., 2009; Reichler & Kim, 2008). The interquartile range of the ensembles was calculated to represent the uncertainties arising from climate models and RCP scenarios. At each river basin, we generated the sequences of MMs of relative runoff change (in the long-term mean and interannual variability) in response to 30 GMT increments (i.e., 30 samples for each basin).

We used the piecewise regression (PLR) model (Toms & Lesperance, 2003) to detect the nonlinearity of runoff response to global warming. The PLR model attempts to detect the potential turning points (TPs; abrupt change) and fits linear trends before and after each TP (see Text S1 in the supporting information). It has been widely used in the fields of ecology (e.g., Ficetola & Denoël, 2010; Piao et al., 2011) and climate change (e.g., Wang et al., 2010). Given the short data records (30 samples), we assume only one TP restricted within the range of 1–2°C GMT rise to ensure that the divided subseries before and after the TP were both long enough (i.e., with 10 samples at least) for robust trend fitting. A decision of nonlinearity is returned when a significant TP is detected at the 95% confidence level (i.e.,  $p$  value < 0.05).

## 3. Results

Figure 1 shows the relative changes in the long-term mean (Figure 1a) and interannual variability (Figure 1b) of global mean runoff in response to the prescribed 30 GMT increments. Results based on the PLR analysis indicate that there is no significant TP in the trend of global runoff change, confirming the linear response of runoff to GMT warming at the global scale as reported by Zhang et al. (2014). Overall, global mean runoff is projected to increase linearly by 2.9% per°C rise of GMT, as indicated by the MMs. Similar finding is also found for the changes in the interannual variability of global runoff, but showing a much larger sensitivity at a rate of 8.8%/°C. This suggests that more risks in hydrological extremes are expected in the future.

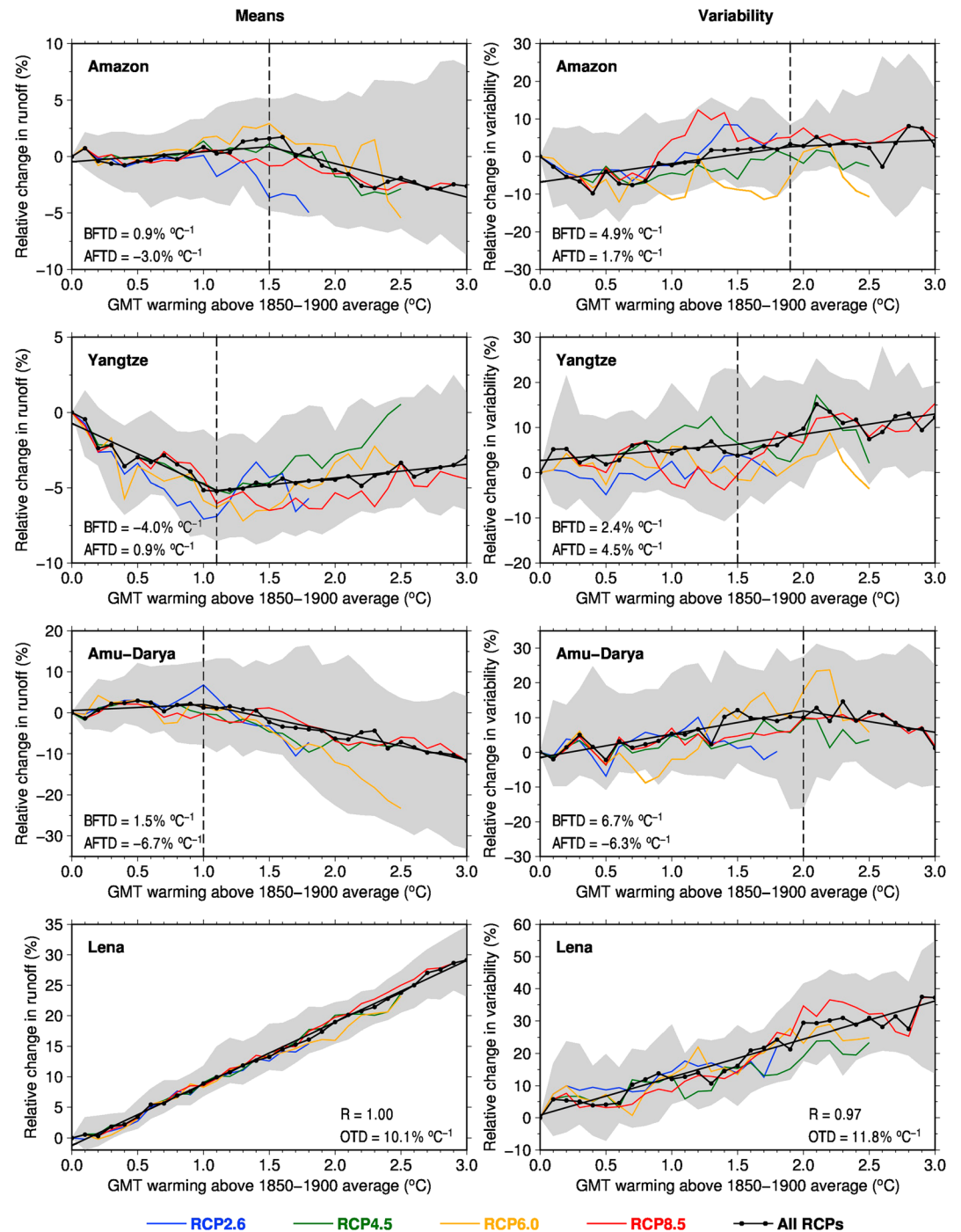


**Figure 1.** Relative changes (%) in (a) means and (b) interannual variability of global mean runoff, estimated as MMs from model subsets across all RCP scenarios at 30 prescribed GMT increments. The shaded area indicates the interquartile range of the ensemble values across all RCPs. The blue line is the linear regression from the MMs ( $R$  is the correlation coefficient; OTD is the magnitude of overall trend).

Figure 2 shows the changes in areal runoff for the selected four representative river basins (i.e., Amazon River, Yangtze River, Amu-Darya River, and Lena River basins), located in tropical rainforest climate zone, temperate monsoon climate zone, arid climate zone, and cold continental climate zone, respectively. It is evident that the response of areal runoff to GMT rise varies greatly among warming levels and river basins. Runoff in Lena River basin is projected to increase by about 10% per°C of global mean warming, independent of emission scenarios. In contrast, significant change points are detected in the tropical Amazon River, monsoon-dominant Yangtze River, and arid Amu-Darya River basin at the 1.5, 1.1, and 1.0°C warming levels, respectively. Specifically, river runoff in Amazon is characterized with a slight increase at a rate of 0.9%/°C when GMT rise is less than 1.5°C, but shows an evident reduction (−3%/°C) afterward. The Yangtze River basin is projected to experience significant drying (−4%/°C) under global warming less than 1.1°C, while a slight wetting (0.9%/°C) is expected to emerge after this warming threshold. A transition from wetting to drying is projected to occur in the arid Amu-Darya River basin when GMT increases by 1.0°C. Overall, the change pattern of runoff response is consistent among RCP scenarios, except for the RCP2.6 (blue line) due to short sample length (i.e., 18). Indeed, most (more than two thirds) of climate models cannot reach the 1.9°C GMT increment by the end of their simulation period under the low emission RCP2.6 scenario. As for the changes in runoff variability, distinct spatial patterns exist at the river basin scale. Specifically, the interannual variability of runoff in Lena River basin tends to increase linearly with GMT rise at a rate of 11.8%/°C. However, nonlinear responses are found in the Amazon River, Yangtze River, and Amu-Darya River basins, as indicated by the significant trend abrupt at the 1.9, 1.5, and 2.0°C GMT rise, respectively.

To explore the possible mechanisms behind the revealed patterns of runoff sensitivity, we repeated our analysis on the response of areal precipitation to GMT rise for the four river basins (Figure S1). The response of precipitation bears an overall resemblance with that of runoff (see Figure 2) over most river basins. The Lena River basin is projected to experience increasing precipitation linearly with rising GMT, while the areal precipitation over Yangtze River basin shows a significant trend transition from downward to upward at 1.1°C GMT warming. Over the Amazon River basin, however, precipitation shows contrasting response to global warming compared to that in runoff (showing significant decrease after 1.5°C GMT rise). This may be associated with the intensified water stress caused by rising temperatures and transpiration rates, widespread deforestation, and climate-change-induced forest retreat (Malhi et al., 2009). As for the interannual variability, a significant change point is detected for all selected river basins, that is, at 1.6°C in Amazon, 1.3°C in Yangtze and Amu-Darya River, and 1.2°C in Lena River basins. This suggests that variability of basin-averaged precipitation varies greatly among different warming levels and river basins.

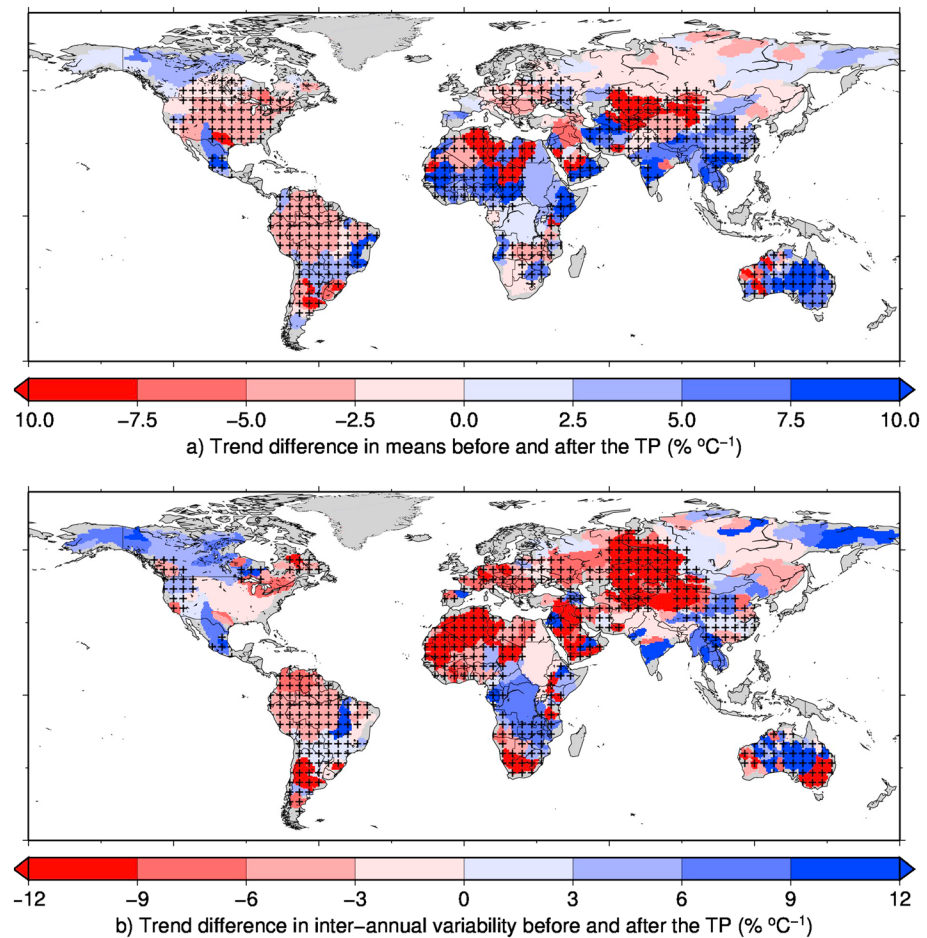
Figure 3 presents the difference between the trends regressed from the divided subseries before and after the TP across the 194 major global river basins. Small difference (less than 3%) in the change rates of runoff is found over much of the high latitudes where no significant TP is detected in the series of runoff change, implying that changes in river runoff can be linearly scaled with GMT warming levels in these basins. In contrast, most of the extended subtropics show considerable trend difference (>3%) before and after the TP, pointing to the nonlinear response of basin-averaged runoff to global warming in these subtropical basins. Globally, such apparent nonlinearities characterized with statistical significant TP ( $p < 0.05$ ) and evident trend difference (>3%) are found over 100 basins, covering over one third (about 35%) of global land surface area (excluding Greenland and Antarctic). Notably, the change trends are observed with reverse signs before (see Figure S2c in the supporting information) and after the TP (see Figure S2e in the supporting information) in the Amazon, Yangtze River, Mississippi River, and other large rivers in southeastern Australia, central Asia, and



**Figure 2.** Relative changes (%) in (left column) means and (right column) interannual variability of basin-averaged runoff estimated as MMs from model subsets of each RCP and across all RCPs over four representative river basins lying in different climate zones. The dashed line indicates the critical GMT warming at which the turning point (TP) is identified; BFTD indicates the magnitude of trend before TP; AFTD indicates the magnitude of trend after TP; OTD indicates the magnitude of overall trend. The shaded area indicates the interquartile range of the ensemble values across all RCPs. Noted that only the warming levels with more than 10 models available are shown for each RCP scenario.

western Africa. As for the interannual variability (Figure 3b), nonlinearities with trend difference larger than 3% are found mainly in central and western Asia, southern and western Africa, most of Europe, and Australia. Overall, significant TP ( $p < 0.05$ ) is detected over 130 river basins, accounting for more than two thirds of global large river basins and covering nearly half (about 45%) of global land surface area

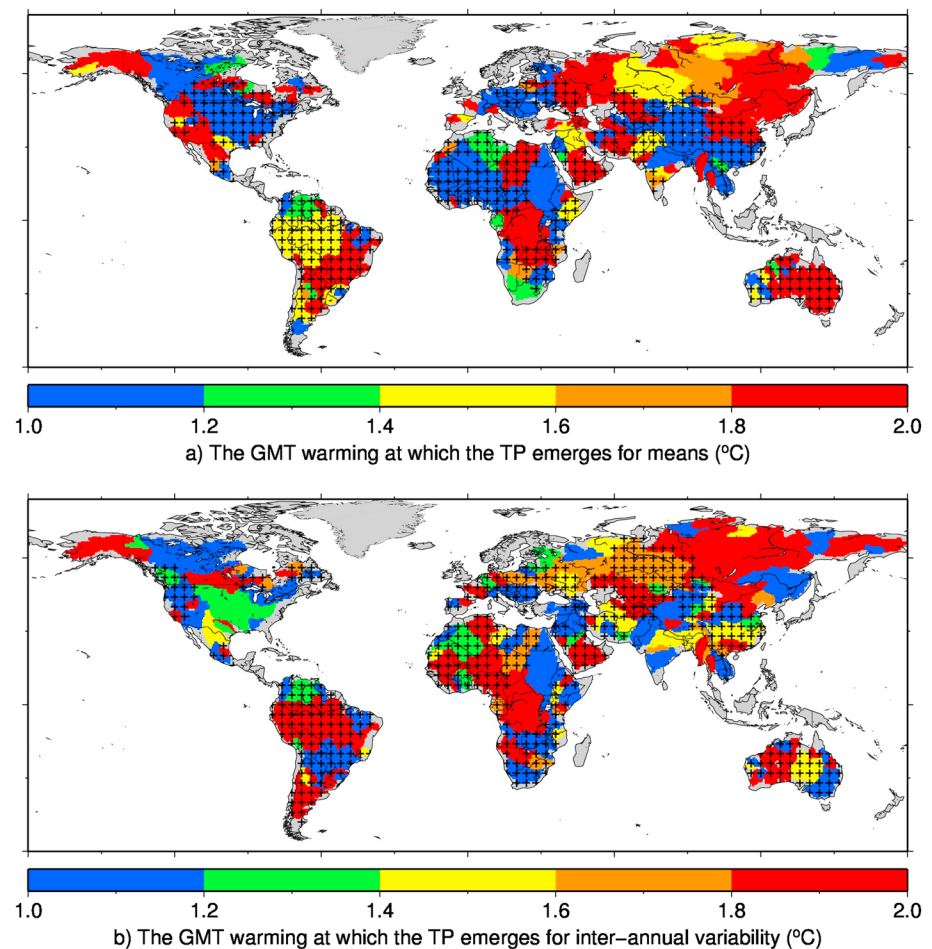




**Figure 3.** Difference (%) between the trends regressed from the divided subseries before and after the turning point (TP) among the 194 global large river basins. (a) Means; (b) interannual variability. The hatched area (“plus sign”) indicates the basins with statistically significant TP detected at the 95% confidence level. The remaining small river basins (not included in the 194 large river basins) and Greenland are masked out with grey colors.

(excluding Greenland and Antarctic). Especially, for those river basins in central Asia and western Africa, the sensitivity of runoff variability in response to GMT change is projected to shift from positive (see Figure S2d in the supporting information) to negative (see Figure S2f in the supporting information), which significantly differs from the mixed pictures derived from the whole series (see Figure S2b in the supporting information). This suggests that variations of trend should not be ignored when projecting future changes in the variability of runoff over those nonlinear basins.

It is of great interest to explore at which level of GMT rise (relative to the preindustrial level) the TP is projected to occur for each river basin. Here the TP is restricted within the range of 1–2°C GMT rise to ensure that the length of divided subseries (before and after TP) are both longer than 10 to allow for reasonable trend estimations. Figure 4a shows the occurrence of detected TP in annual mean runoff. In general, the detected TPs with statistical significance ( $p < 0.05$ ; see hatched area in Figure 4a) mostly falls into the start- or end-point warming levels, that is, around 1°C in Southeast and central Asia, North America, and North Africa, or around 2°C in Australia, North China, and U.S. Southwest. The nonlinearities emerging at the two ends suggest that the hydrologic trend derived from the past 30-year period with global mean surface temperature 0.78°C warmer than that for 1850–1900 (IPCC, 2014) could not be used for extrapolating the potential future change. Figure 4b shows that the significant TP (see hatched area in Figure 4b) in the trend of runoff variability is primarily detected at the warming level beyond 1.5°C in more than half (about 56%) of the global major river basins, suggesting that impacts of 1.5°C global warming may not be scaled directly from previous assessments for the 2°C warming target in these basins.



**Figure 4.** The threshold of GMT warming (relative to the preindustrial level) when the TP in runoff series emerges. (a) Means; (b) interannual variability. The hatched area ("plus sign") indicates the basins with statistically significant TP detected at the 95% confidence level. The remaining small river basins (not included in the 194 large river basins) and Greenland are masked out with grey colors.

#### 4. Conclusions and Discussion

Our results show that changes in the long-term mean and interannual variability of runoff are approximately linear with GMT rise at the global scale. However, changes in runoff differ greatly among river basins, showing nonlinear response to GMT rise in most extended subtropical basins where significant change points are detected. In particular, the trends before and after the TP show opposite signs in major rivers in South and central Asia, southeastern Australia, and western Africa. The fact that the nonlinearities tend to emerge at the end-point warming levels implies that future hydrological impacts of anthropogenic climate change cannot be extrapolated from the change trend of runoff during the past 30 years with global mean surface temperature being  $0.78^{\circ}\text{C}$  warmer than that during 1850–1900 (IPCC, 2014). As for the interannual variability, nonlinearities are primarily found in central and western Asia, southern and western Africa, most of Europe, and Australia with TP detected at GMT rise beyond  $1.5^{\circ}\text{C}$ . Our results point to the necessity to reevaluate the impacts of  $1.5^{\circ}\text{C}$  GMT warming, rather than inferring from previous assessments under the  $2^{\circ}\text{C}$  warming scenario.

The nonlinear response of basin-scale runoff to global warming may be attributed to the validity of assumptions behind the Clausius-Clapeyron law. Theoretically, saturation water vapor is expected to increase by about 7% for each  $1^{\circ}\text{C}$  temperature increase following the Clausius-Clapeyron scaling rule. Assuming that the relative humidity is unchanged and the flow is unchanged, the water budget (evaporation minus precipitation) would increase linearly with enhanced lower-tropospheric vapor associated with rising GMT (Held &

Soden, 2006). However, such assumptions, in most cases, do not hold at the river basin scale. For instance, in the Amazon River basin, there has been evidence for the climate-vegetation feedback. The climate-change-induced large-scale degradation of rainforest may alter regional atmospheric circulation via land-atmosphere feedback mechanism, resulting in intensification of seasonal water stress and thus drier conditions at higher warming degree (Malhi et al., 2009).

In contrast with previous studies focusing on the linkage of global mean runoff and GMT (Tang & Lettenmaier, 2012; Zhang et al., 2014), this study provides valuable insights on the response of areal runoff to global warming at the river basin scale. We highlight the river basins and the threshold of GMT increment where and when the nonlinearity of runoff response emerges across the 194 major river basins globally. The revealed nonlinear response of regional runoff to global warming advances our understanding on the contrasting climate impacts under various warming levels, which has great implications for local climate mitigation and adaptation.

### Acknowledgments

Funding for this research is provided by the National Natural Science Foundation of China (grants 41730645, 41790424, and 41425002), Chinese Postdoctoral Science Foundation (2016M601117), the Key Research Program of the Chinese Academy of Sciences (ZDRW-ZS-2017-4 and KGFZD-135-17-009-3), and the National Youth Top-notch Talent Support Program in China. All the data used in this study are open-available in the Program for Climate Model Diagnosis and Intercomparison (PCMDI; <http://pcmdi9.llnl.gov/>). The authors declare no conflict of interest.

### References

- Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Climatic Change*, 134(3), 387–401. <https://doi.org/10.1007/s10584-014-1084-5>
- Donnelly, C., Greuell, W., Andersson, J., Gerten, D., Pisacane, G., Roudier, P., & Ludwig, F. (2017). Impacts of climate change on European hydrology at 1.5, 2 and 3 degrees mean global warming above preindustrial level. *Climatic Change*, 143(1-2), 13–26. <https://doi.org/10.1007/s10584-017-1971-7>
- Ficetola, G. F., & Denoël, M. (2010). Ecological thresholds: An assessment of methods to identify abrupt changes in species-habitat relationships. *Ecography*, 32(6), 1075–1084. <https://doi.org/10.1111/j.1600-0587.2009.05571.x>
- Gosling, S., Zaherpour, J., Mount, N. J., Hattermann, F. F., Dankers, R., Arheimer, B., et al. (2017). A comparison of changes in river runoff from multiple global and catchment-scale hydrological models under global warming scenarios of 1 °C, 2 °C and 3 °C. *Climatic Change*, 141(3), 577–595. <https://doi.org/10.1007/s10584-016-1773-3>
- Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., et al. (2014). Global water resources affected by human interventions and climate change. *Proceedings of the National Academy of Sciences of the United States of America*, 111(9), 3251–3256. <https://doi.org/10.1073/pnas.1222475110>
- Held, I. M., & Soden, B. J. (2006). Robust responses of the hydrological cycle to global warming. *Journal of Climate*, 19(21), 5686–5699. <https://doi.org/10.1175/JCLI3990.1>
- IPCC (2014). Climate change 2013: The physical science basis. In T. F. Stocker, et al. (Eds.), *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 159–254). Cambridge, UK and New York: Cambridge University Press. <https://doi.org/10.1017/CBO9781107415324>
- Knutti, R., Rogelj, J., Sedláček, J., & Fischer, E. M. (2016). A scientific critique of the two-degree climate change target. *Nature Geoscience*, 9(1), 13–18. <https://doi.org/10.1038/NGEO2595>
- Leng, G., Huang, M., Voisin, N., Zhang, X., Asrar, G. R., & Leung, L. R. (2016). Emergence of new hydrologic regimes of surface water resources in the conterminous United States under future warming. *Environmental Research Letters*, 11(11), 114003. <https://doi.org/10.1088/1748-9326/11/11/114003>
- Leng, G., Tang, Q., Huang, S., Zhang, X., & Cao, J. (2016). Assessments of joint hydrological extreme risks in a warming climate in China. *International Journal of Climatology*, 36(4), 1632–1642. <https://doi.org/10.1002/joc.4447>
- Malhi, Y., Aragão, L. E. O. C., & Galbraith, D. (2009). Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America*, 106(49), 20,610–20,615. <https://doi.org/10.1073/pnas.0804619106>
- Marx, A., Kumar, R., Thober, S., Zink, M., Wanders, N., Wood, E. F., et al. (2017). Climate change alters low flows in Europe under a 1.5, 2, and 3 degree global warming. *Hydrology and Earth System Sciences Discussions*, 1–24. <https://doi.org/10.5194/hess-2017-485>
- Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., et al. (2009). Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, 458(7242), 1158–1162. <https://doi.org/10.1038/nature08017>
- Milly, P. C. D., Dunne, K. A., & Vecchia, A. V. (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, 438(7066), 347–350. <https://doi.org/10.1038/nature04312>
- Mote, P., Brekke, L., Duffy, P. B., & Maurer, E. (2011). Guidelines for constructing climate scenarios. *Eos Transactions American Geophysical Union*, 92(31), 257–258. <https://doi.org/10.1029/2011EO310001>
- Nohara, D., Kitoh, A., Hosaka, M., & Oki, T. (2006). Impact of climate change on river discharge projected by multimodel ensemble. *Journal of Hydrometeorology*, 7(5), 1076–1089. <https://doi.org/10.1175/JHM531.1>
- Piao, S., Wang, X., Ciais, P., Zhu, B., Wang, T., & Liu, J. (2011). Changes in satellite-derived vegetation growth trend in temperate and boreal Eurasia from 1982 to 2006. *Global Change Biology*, 17(10), 3228–3239. <https://doi.org/10.1111/j.1365-2486.2011.02419.x>
- Pierce, D. W., Barnett, T. P., Santer, B. D., & Gleckler, P. J. (2009). Selecting global climate models for regional climate change studies. *Proceedings of the National Academy of Sciences of the United States of America*, 106(21), 8441–8446. <https://doi.org/10.1073/pnas.0900094106>
- Reichler, T., & Kim, J. (2008). How well do coupled models simulate today's climate? *Bulletin of the American Meteorological Society*, 89(3), 303–312. <https://doi.org/10.1175/BAMS-89-3-303>
- Roudier, P., Andersson, J. C. M., Donnelly, C., Feyen, L., Greuell, W., & Ludwig, F. (2016). Projections of future floods and hydrological droughts in Europe under a +2°C global warming. *Climatic Change*, 135(2), 341–355. <https://doi.org/10.1007/s10584-015-1570-4>
- Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., et al. (2014). Multi-model assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, 111(9), 3245–3250. <https://doi.org/10.1073/pnas.1222460110>
- Singh, C. R., Thompson, J. R., French, J. R., Kingston, D. G., & Mackay, A. W. (2010). Modelling the impact of prescribed global warming on runoff from headwater catchments of the Irrawaddy River and their implications for the water level regime of Loktak Lake, northeast India. *Hydrology and Earth System Sciences*, 14(9), 1745–1765. <https://doi.org/10.5194/hess-14-1745-2010>

- Tang, Q., & Lettenmaier, D. P. (2012). 21st century runoff sensitivities of major global river basins. *Geophysical Research Letters*, 39, L06403. <https://doi.org/10.1029/2011GL050834>
- Tang, Q., & Oki, T. (2016). *Terrestrial water cycle and climate change: Natural and human-induced impacts*, AGU Geophysical Monograph Series (Vol. 221). Hoboken, NJ: John Wiley. <https://doi.org/10.1002/9781118971772>
- Toms, J. D., & Lesperance, M. L. (2003). Piecewise regression: A tool for identifying ecological thresholds. *Ecology*, 84(8), 2034–2041. <https://doi.org/10.1890/02-0472>
- United Nations Framework Convention on Climate Change (2015). Adoption of the Paris agreement, Proposal by the President, Tech. rep., United Nations, Geneva, Switzerland.
- United Nations Framework Convention on Climate Change (2010). Report of the Conference of the Parties on its sixteenth session. Available from <http://unfccc.int/resource/docs/2010/cop16/eng/07a01.pdf>. United Nations, Geneva, Switzerland.
- Vörösmarty, C. J., Fekete, B. M., Meybeck, M., & Lammers, R. B. (2000). Global system of rivers: Its role in organizing continental land mass and defining land-to-ocean linkages. *Global Biogeochemical Cycles*, 14(2), 599–621. <https://doi.org/10.1029/1999GB900092>
- Wang, S., Wang, Z., Piao, S., & Fang, J. (2010). Regional differences in the timing of recent air warming during the past four decades in China. *Chinese Science Bulletin*, 55(19), 1968–1973. <https://doi.org/10.1007/s11434-010-3236-y>
- Yang, H., Zhou, F., Piao, S., Huang, M., Chen, A., Ciais, P., et al. (2017). Regional patterns of future runoff changes from Earth system models constrained by observation. *Geophysical Research Letters*, 44, 5540–5549. <https://doi.org/10.1002/2017GL073454>
- Zaherpour, J., Gosling, S., Mount, N., Gerten, D., Schmied, H., Kim, H., et al. (2018). Worldwide evaluation of mean and extreme runoff from six global-scale hydrological models that account for human impacts. *Environmental Research Letters*. <https://doi.org/10.1088/1748-9326/aac547>
- Zhang, X., Tang, Q., Zhang, X., & Lettenmaier, D. P. (2014). Runoff sensitivity to global mean temperature change in the CMIP5 models. *Geophysical Research Letters*, 41, 5492–5498. <https://doi.org/10.1002/2014GL060382>