

Responses of water resource of the Yarlung Zangbo River Basin to climate changes and glacier-snow fluctuations in recent years

N Nie^{1,2}, W C Zhang^{2,3} and C Deng^{1,2}

¹ State Key Laboratory of Pollution Control & Resource Reuse, School of the Environment, Nanjing University, Nanjing 210023, China.

² Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100094, China.

E-mail: zhangwc@radi.ac.cn

Abstract. Responses of river water resource of the Yarlung Zangbo River (YR) Basin to climate change and glacier-snow fluctuations in recent years were systematically studied by taking the best use of meteorological data and remote sensing images. Climate variation trends over the YR basin, mainly focusing on temperature, precipitation and actual evapotranspiration during 1979-2006, were examined by means of the GIS spatial interpolation techniques, meteorological statistics analyses, Mann-Kendall nonparametric test, etc. Based on the daily snow depth dataset derived from SMMR and SSM/I, annual snow-cover days and average snow depth (maximum and mean) were collected and analysed in the YR basin during 1979-2006. According to the water budget for a closed watershed, in association with the relevant achievements obtained from pioneer studies, the response of river water resources to the variation of climate, glaciers and snow cover in the YR basin was systematically studied. The results suggest that, under the background of the increasing temperature, precipitation, actual evapotranspiration and glacier melting together with the decreasing snow cover over the basin, river runoff presented the increasing trend to respond the climate and glacier changes at the speed of $18.7 \text{ m}^3 \text{ s}^{-1} \text{ a}^{-1}$ with the significant level of $\alpha < 0.1$ from 1979 to 2006.

1. Introduction

As the highest great river in the world with a mean elevation of over 4000 m [1], the Yarlung Zangbo River (YR) Basin is also one of the major maritime glacier developed regions with abundant solid (glaciers and snow) and liquid (stream flow) water resource in China. The water resources in this region are of great importance for both China and India. Prior studies have shown that the climate, glacier, snow cover and water resources over the YR basin have changed under the background of global change. However, due to the special geographical location of the YR basin, many difficulties existed for logistic support of field observations in the region, and comprehensive and systematical study on the climate change, glacier-snow fluctuations and the corresponding response of river water resource over the whole basin was difficult to conduct. This study is attempted to take the best use of meteorological data, basic geographic information, and daily snow cover datasets derived from

³ To whom any correspondence should be addressed.



SMMR and SSM/I collected in the YR Basin, in association with the relevant achievements obtained from pioneer studies in the region, under the principle of water budget for a closed watershed, to explore the responses of river water resource to climatic and glacier-snow changes of the whole basin.

2. Data and methods

2.1. Data

Climatic data from meteorological stations located over the YR basin obtained from China Meteorological Data Sharing Service System were analyzed. Climatic variation trends over the YR basin from 1979 to 2006 for air temperature and precipitation collected from 27 meteorological stations as the geographic locations illustrated in figure 1 were explored.

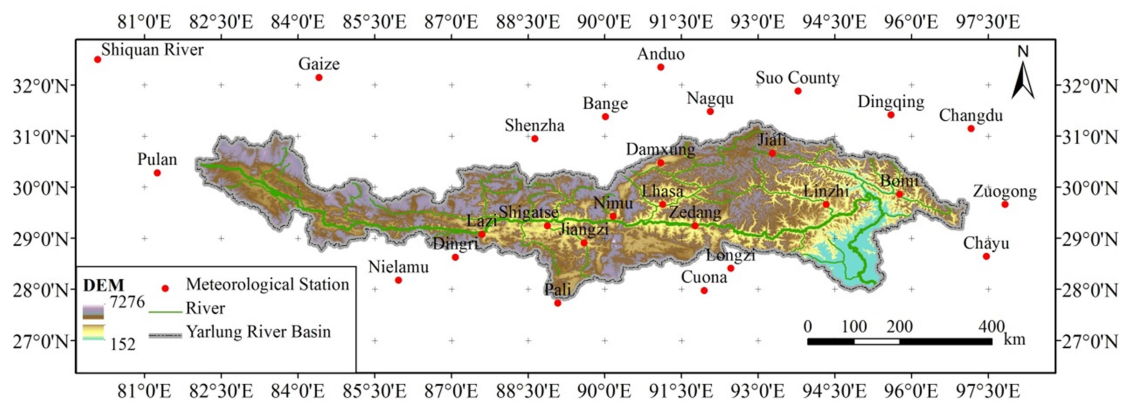


Figure 1. Map showing fundamental geographic information of the YR Basin.

Studies suggested that Takahashi Formula estimated actual evapotranspiration had large bias compared with the observations over the Qinghai Tibet Plateau because of the effects of frozen soil and snow thaw on the Plateau [2]. By introducing a coefficient on the precipitation part without changing the original form of Takahashi Formula, Fu et al.[2] amended the formula as shown in equation (1) for accurate estimation of actual evapotranspiration in Lhasa.

$$E = \frac{3100(P + X)}{3100 + 1.8P^2 \exp\left(\frac{-34.4T}{235 + T}\right)} \quad \begin{array}{ll} T \leq 0^\circ\text{C}, X = 5 & 10^\circ\text{C} < T \leq 15^\circ\text{C}, X = 15 \\ 0^\circ\text{C} < T \leq 5^\circ\text{C}, X = 10 & T > 15^\circ\text{C}, X = 80 \\ 5^\circ\text{C} < T \leq 10^\circ\text{C}, X = 20 & \end{array} \quad (1)$$

Here E indicates monthly actual evapotranspiration, P and T represents monthly precipitation and air temperature respectively. In this study, we selected equation (1) to calculate monthly actual evapotranspiration over the YR Basin. Annual actual evapotranspiration was obtained by adding monthly result of a year.

With a 7-channel 4-frequency radiometer, SMMR and SSM/I have been utilized for retrieval of various snow parameters. The daily snow depth derived from SMMR (from 1979 to 1987) and SSM/I (from 1987 to 2006) radiometric data for China can be downloaded from <http://westdc.westgis.ac.cn>. The algorithms and computation flow for this dataset can be found in the literature of [3] and [4]. Based on the daily snow depth dataset, annual snow-cover days and average snow depth (maximum and mean) were analyzed by using RS and GIS techniques with special attentions being paid on snow covers in the YR basin during 1979-2006.

2.2. Methodology

Common interpolation methods, such as Inverse Distance Weighting (IDW), Kriging and Spline, were applied to obtain the spatial distribution of climatic elements (temperature and precipitation), among which IDW was demonstrated the best in the YR basin [5]. Therefore, IDW was applied to obtain the spatial distribution of climatic elements in this study. Linear regression analysis (least squares method)

and Mann-Kendall nonparametric test method were used to detect possible long-term trends and significant level of variations in time series of metrological parameters. In the Mann-Kendall test, null hypothesis H_0 is that the data ($X_1, X_2 \dots X_n$) is a sample of n independent and identically distributed random variables. The alternative hypothesis H_1 of a two-sided test states that the distributions of X_k and X_j are not identical for all k, j . The Mann-Kendall test may be simply stated as follows:

Null hypothesis: H_0 . Significance level: α . Test statistics: Z_c .

Rejected H_0 : $|Z_c| > |Z_{1-\alpha/2}|$, in which $Z_{1-\alpha/2}$ is the standard normal deviation and α represents the significance level of the test. The principle and the calculation steps of this method can be found in the literature of [6] and [7].

3. Results and discussion

3.1. Climate change

Time series of spatial annual mean temperature, precipitation and actual evapotranspiration during 1979-2006 over the YR basin were derived with the methodology as described in the previous section. Linear regression analysis (least squares method) and Mann-Kendall nonparametric test method were adopted to detect possible long-term trends and significant levels of variations on these meteorological parameters, and the results were shown in figure 2.

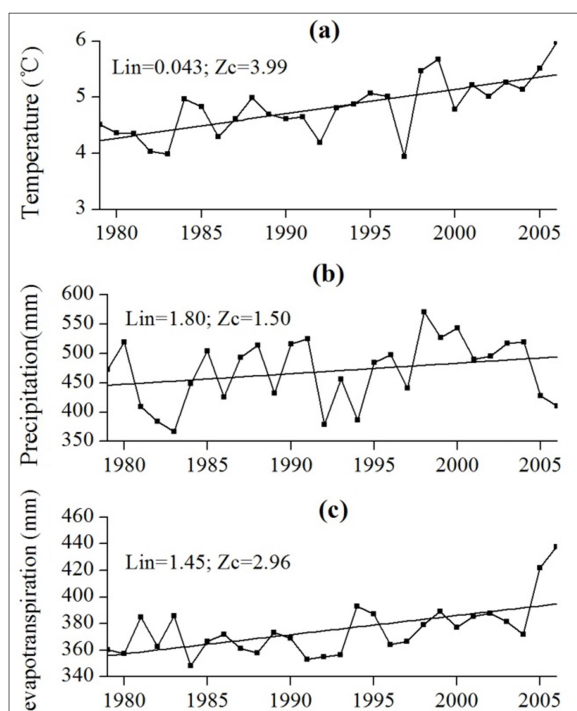


Figure 2. Variation trends of annual mean air temperature (a), precipitation (b) and actual evapotranspiration (c) over the YR basin in period of 1979–2006. The straight line represents linear trends, and Lin stands for linear-change-rate and Z_c for Mann-Kendall test statistics.

From figure 2a, it can be seen that annual air temperature for the YR basin as a whole during 1979-2006 had increased about 1.2°C at a speed of $0.43^\circ\text{C}/10\text{a}$. The warming trend was very obvious with the significant level of $\alpha < 0.001$. Yang et al. [8] indicated that during the period of 1971-2004, the linear increasing rate of air temperature averaged in China and globally was about 0.226°C and

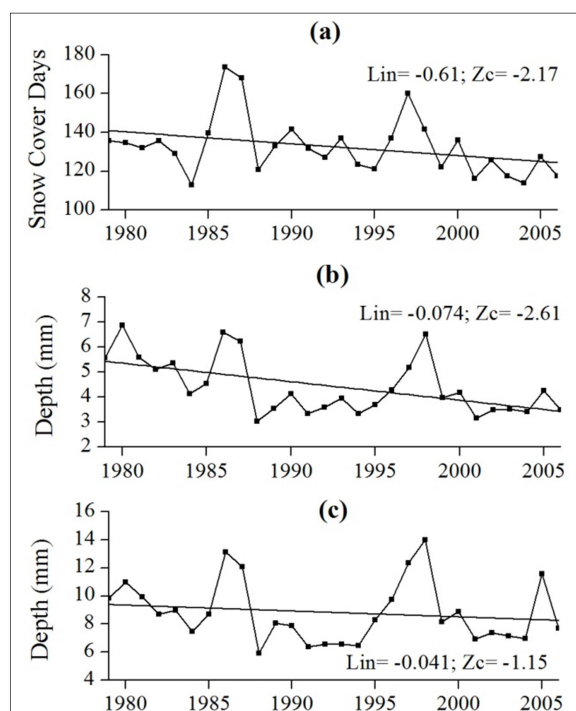


Figure 3. Same as figure 2 but for snow cover days (a), mean snow depth (b) and maximum snow depth (c) averaged over the YR basin from 1979 to 2006.

0.148°C/decade respectively. The linear increasing rate of air temperature averaged in the YR Basin was significantly higher than those for China and for the world in the same period. Statistical analyses on annual mean precipitation averaged for the YR basin suggested a slightly increasing period from 1992 to 1999 with a speed of 21.2mm/a and a slowly decreasing period from 2000 to 2006 with a speed of -17.7mm/a (figure 2b). In general, annual mean precipitation averaged in the basin exhibited a non-significant increasing trend of 18.0 mm/decade with the significant level of $\alpha > 0.1$ during the period 1979-2006. Annual mean actual evapotranspiration experienced a decreasing trend during the period 1979-1993 and then exhibited an increasing trend afterwards (figure 2c). Generally, annual mean actual evapotranspiration averaged over the basin from 1979 to 2006 showed a significant increasing trend with speed of 14.5 mm/decade under the significant level of $\alpha < 0.01$.

3.2. Variation of snow cover

Annual snow-cover days and maximum and mean snow depth, derived from SMMR and SSM/I data by means of GIS spatial analysis techniques, averaged over the basin during 1979-2006 were illustrated in figure 3 for variation trends analysis. According to figure 3a, we can find that there were more than 110 days snowpack covered on average over the YR basin. The linear decreasing trend of snow-cover days for the YR basin during the period 1979-2006 can be detected at speed of -6 days/10a with the significant level of $\alpha < 0.05$. Meanwhile, mean and maximum snow depth became thinner at the speed of -0.74mm/10a (with the significant level of $\alpha < 0.01$) and -0.41mm/10a, respectively (figures 3b and 3c). As a consequence, it is believed that snow meltwater probably decreased over the YR basin during the past 30 years.

Table 1. Changes of glaciers in representative regions in YR Basin during the past few decades.

Study Area	Period /year	Number of Glaciers Studied	Area Change / km ²	Proportion of Area Change / %	Source of Data	Notes
Gangrigabu Range	1980-2001	88	-2.02	-0.25	[9]	24 glaciers over the Ranwu Lake Basin and 64 glaciers over the Danlongqu Basin; Maritime Glaciers
Ranwu Lake Basin	1980-2005	All Glaciers over This Basin	-29.7	-5.98	[10]	Maritime Glaciers
Nianchuhe River Basin	1980-2005	83	-13.41	-7.3	[11]	Continental Glaciers
YR Basin	1976-2005	21	-17.9	-1.25	[12]	Large Maritime Glaciers
Jiema Yangzong Glacier	1974-2010	1	-1.11	-5.10	[13]	The source of Yarlung Zangbo River; Continental glacier on the east side of ridge, and maritime glacier on the west side of ridge
Zhadang Glacier	2005-2008	1	Annual glacier mass balance was -1143, -838, 208 mm.w.e. from 2005 to 2008, respectively.		[14]	Field Measurements; Continental Glacier

3.3. Glacier fluctuations

Table 1 summarized the glacier mass balance measurement results reported in different literatures concerning with the YR basin glacier studies. Glaciers listed in Table 1 of which total area accounting for about 21% of that in the whole basin in 1976, are different in the size (big or small), characteristic (continental glacier or maritime glacier) and geographical location (upstream, midstream and downstream). Therefore, trends for variation of these glaciers were representative enough for that of

the glaciers over the whole YR basin in past decades. According to these previous studies, we can find that most glaciers in the YR basin tended to retreat in general since the late 1970s. As a consequence, it was believed that glacial meltwater might increase over the YR basin in past decades.

3.4. Response of river water resource to climate and glacier-snow changes over the region

Theoretically, if the water consumptions for human activities are less enough to be neglected, the multi-year water balance equation for YR basin can be expressed as [15]:

$$P + S + G - E = R \quad (2)$$

in which P , S , G , E and R are precipitation, snow meltwater, glacier meltwater, actual evapotranspiration and runoff during a period, respectively.

Considering the glacier meltwater directly influenced by climate factors such as temperature, precipitation and so on, in association with Equation (2), changes of temperature, precipitation, actual evapotranspiration and glacier-snow were directly related to the variation of watershed runoff. Correlation analysis between runoff and these factors during 1979-2006 was shown in Table 2. The observed runoff data of Nuxia hydrometric station (29.14°N, 94.34°E) located in the downstream of YR basin was obtained from literature [16]. Variation of the runoff measured by Nuxia hydrometric station of which controlling area accounts for 70% of the whole watershed area can represent the change trend of the river water resource.

Table 2. Correlation analysis between runoff and relevant factors (temperature, precipitation, actual evapotranspiration and snow cover).

	P	T	E	Snowcover Day	Maximum Snowdepth	Mean Snowdepth
Correlation Coefficient	0.871	0.444	0.006	-0.077	0.138	0.029
Significance	$\alpha < 0.01$	$\alpha < 0.05$	/	/	/	/

Correlation coefficient of precipitation-runoff and temperature-runoff were 0.871 and 0.444 with the significant level of $\alpha < 0.01$ and $\alpha < 0.05$, respectively (Table 2). However, river runoff has the poor correlations with actual evapotranspiration and snow cover. It suggested that the precipitation and glacier meltwater were the main sources of YR water resource supplies. Although watershed evapotranspiration increased and snow cover decreased in recent years, the river runoff increased at a speed of $18.7 \text{ m}^3 \text{ s}^{-1} \text{ a}^{-1}$ during 1979-2006 with the significant level of $\alpha < 0.1$ under the background of the increasing precipitation, temperature and glacier meltwater.

4. Conclusions

According to previous studies plus present result obtained in this study, the response of river water resources to the climate, glaciers and snow cover changes in the YR basin was systematically studied. From 1979 to 2006, under the background of the increasing temperature, precipitation, actual evapotranspiration and glacier meltwater and decreasing snow cover over the basin, river runoff presented the increasing trend to respond the climate and glacier changes at the speed of $18.7 \text{ m}^3 \text{ s}^{-1} \text{ a}^{-1}$ with the significant level of $\alpha < 0.1$.

Acknowledgements

This work was financially supported by the National Key Technologies R&D Program of China (No. 2016YFA0602302 and No. 2016YFB0502502), and CRSRI Open Research Program (CKWV2015226/KY), respectively.

References

- [1] You Q, Kang S, Wu Y and Yan Y 2007 Climate change over the Yarlung Zangbo River Basin

- during 1961-2005 *J. Geogr. Sci.* **17** 409-20
- [2] Fu J, Fan G Z and Zhou D W 2012 The applicability and modification of Takahashi formula for evaporation estimation in Lhasa *Journal of Applied Meteorological Science* **23** 231-7
- [3] Che T, Li X, Jin R, Armstrong R and Zhang T 2008 Snow depth derived from passive microwave remote-sensing data in China *Ann. Glaciol.* **49** 145-54
- [4] Bi X and Zhang W 2009 Long term analyses on spatial and temporal evaluation of snow covers in northern China by using RS and meteorological data. In: *2008 International Workshop on Education Technology and Training and 2008 International Workshop on Geoscience and Remote Sensing, Vol 2, Proceedings*, ed L Qi p 368-71
- [5] Nie N, Zhang W and Deng C 2012 Spatial and temporal climate variations from 1978 to 2009 and their trend projection over the Yarlung Zangbo River Basin *Journal of Glaciology and Geocryology* **34** 64-71
- [6] Belle G V and Hughes J P 1984 Nonparametric tests for trend in water quality *Water Resour. Res.* 127-36
- [7] Wei F 2007 *Modern Climatic Statistical Diagnosis and Prediction Technology* (Beijing: China Meteorological Press)
- [8] Yang X, Zhang Y, Zhang W, Yan Y, Wang Z, Ding M and Chu D 2006 Climate change in Mt.Qomolangma region since 1971 *J. Geogr. Sci.* **16** 326-36
- [9] Liu S, Shangguan D, Ding Y, Han H, Zhang Y, Wang J, Xie C, Ding L and Li G 2005 Glacier variations since the early 20th century in the Gangrigabu range, southeast Tibetan Plateau *Journal of Glaciology and Geocryology* **27** 55-63
- [10] Xin X, Yao T, Ye Q, Guo L and Yang W 2009 Study of the fluctuations of glaciers and lakes around the Ranwu Lake of southeast Tibetan Plateau using remote sensing *Journal of Glaciology and Geocryology* **31** 19-26
- [11] Li Z, Yao T, Ye Q, Tian L and Wang W 2010 Glaciers in the upstream Manla Reservoir in the Nianchu river basin, Tibet: shrinkage and impact *Journal of Glaciology and Geocryology* **32** 650-8
- [12] Nie N, Zhang Z, Zhang W and Deng C 2013 Analysis of the characteristics of the glacier change based on remote sensing in the Yarlung Zangbo River basin during the past 30 years *Journal of Glaciology and Geocryology* **35** 541-52
- [13] Liu X and Xiao C 2011 Preliminary study of the Jiemayangzong Glacier and lake variations in the source regions of the Yarlung Zangbo River in 1974-2010 *Journal of Glaciology and Geocryology* **33** 488-96
- [14] Yao T D, Li Z G, Yang W, Guo X J, Zhu L P, Kang S C, Wu Y H and Yu W S 2010 Glacial distribution and mass balance in the Yarlung Zangbo River and its influence on lakes *Chin. Sci. Bull.* **55** 2072-8
- [15] Rui X F 2004 *The Principle of Hydrology* (Beijing: China Water & Power Press)
- [16] Luozhu Nima, Wang J and Xu X 2011 Variation characteristics and trend analysis of runoff over the Yarlung Zangbo River Basin *Journal of China Hydrology* **31** 76-9