Impact analysis of climate change on snowfall and fractional snow cover over a complex mountainous region using a numerical model and remote sensing products

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Abstract: The effect of climate change on snow is complex at the regional scale. The increasing or decreasing trends of snow under a climate change at some regions remain unknown. Here, we used high spatiotemporal resolution snow-related variables simulated by a weather research and forecast model (including snowfall, snow water equivalent and snow depth) and fractional snow cover (FSC) data extracted from MODIS/Terra to evaluate the effects of climate change on snow over the Heihe River Basin (HRB), a typical endorheic river basin in arid region of northwest China from 2000 to 2013 using Empirical Orthogonal Function (EOF) analysis and Mann-Kendall/Theil-Sen trend analysis. The results are as follows: 1) The FSC, snow water equivalent, and snow depth across the entire HRB region decreased, especially at elevations over 4,500 m; however, the snowfall increased at mid-altitude ranges in the upstream area of the HRB. 2) The total snowfall also increased in the upstream area of the HRB; however, the number of snowfall days decreased. Therefore, the number of extreme snow events upstream of the HRB may have increased. 3) The snowfall over the downstream area of the HRB decreased.

Research region: The study area is the Heihe River Basin, which has been taken as an ideal test bed and field laboratory for land surface or hydrological experiments. From the upper reaches to the lower reaches, there are distributed glacier, permafrost, oasis, bare and Gobi desert areas.

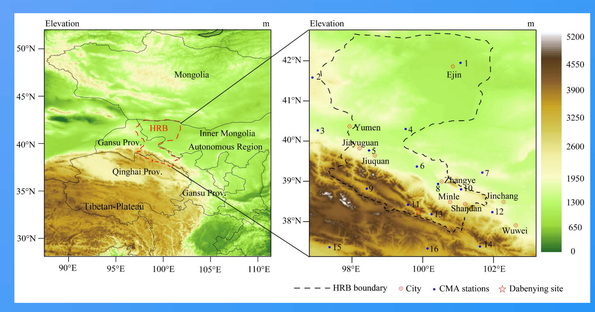

Figure 1. Study region and observation situ

Data: precipitation, snowfall, snow water equivalent and snow depth are simulated by WRF model, FSC is retrieved from MODIS/Terra.

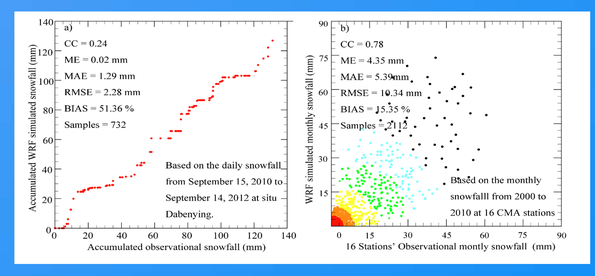

Figure 2. Snowfall evaluation

We use the satellite-retrieved snow cover product supplemented by variables simulated by the WRF model to determine whether climate change has occurred over the HRB and to evaluate the relationship between snowfall and climate change over the HRB with the goal of answering the research questions listed above.

Methods: Empirical Orthogonal Function Analysis and Mann-Kendall/Theil-Sen Trend Analysis

$$F_{ijk} = F(t_i, \theta_j, \emptyset_k) \qquad X' = X - (1, \dots, 1)^T \overline{X} = (I - \frac{1}{n}(1, \dots, 1)(1, \dots, 1)^T)X$$

$$X = \begin{pmatrix} x_{11} & \cdots & x_{1p} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{np} \end{pmatrix} \qquad \Sigma = \frac{1}{n-1} X'^T X'$$

$$\overline{x} = (\overline{x}_{.1}, \dots, \overline{x}_{.p}) \qquad \max_a \left(a^T \sum a \right), s.t. a^T a = 1$$

$$\text{var}(X'a) = \frac{1}{n-1} \|X'a\|^2 = \frac{1}{n-1} (X'a)^T (X'a) = a^T \sum a$$

$$\sum a = \lambda a \qquad \frac{100\lambda_k}{\sum_{k=1}^{p} \lambda_k} \%$$

Mann-Kendall/Theil-Sen Trend Analysis

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i)$$

$$sgn(x_j - x_i) = \begin{cases} +1, if\ x_j - x_i > 0 \\ 0, if\ x_j - x_i = 0 \\ -1, if\ x_j - x_i < 0 \end{cases}$$

$$Z_S = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, if\ S > 0 \\ 0, if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, if\ S < 0 \end{cases}$$

$$Y_t = \alpha + \beta t + \varepsilon_t$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i (t_i - 1)(2t_i + 5)}{18}$$

Results & Conclusion

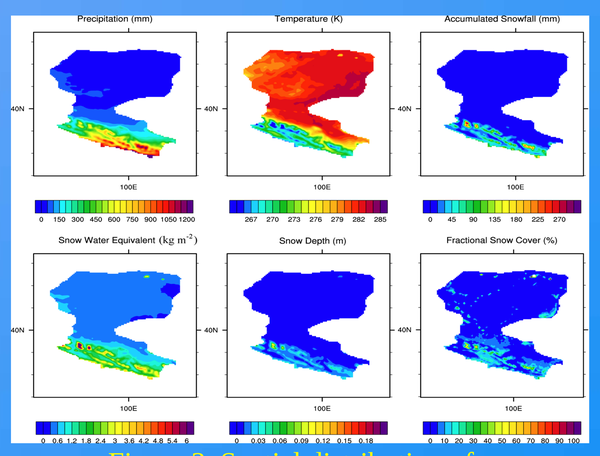

Figure 3. Spatial distribution of annual variables from 2000 to 2013.

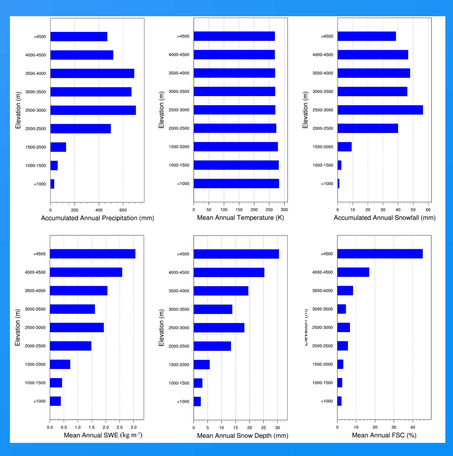

Figure 4. Altitudinal profiles of annual variables from 2000 to 2013.

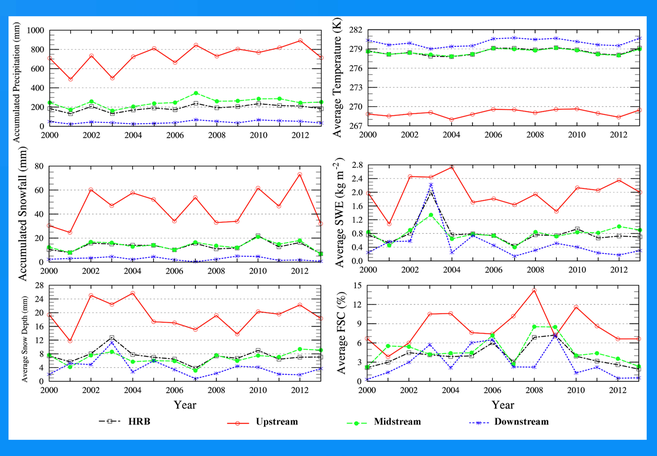

Figure 5. Annual variables over the HRB and its sub-regions from 2000 to 2013.

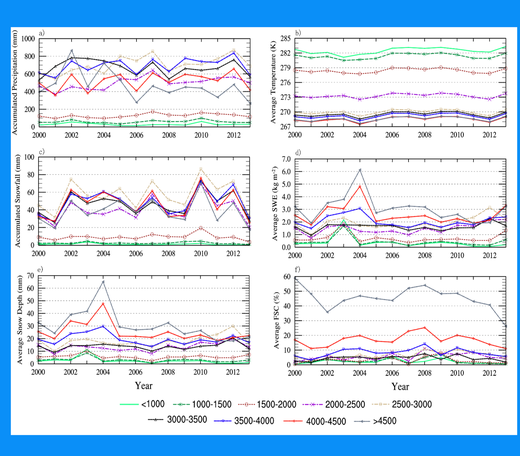

Figure 6. Annual variables by altitude from 2000 to 2013.

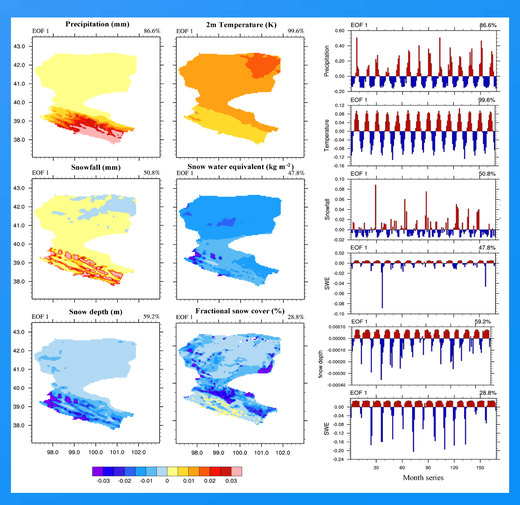

Figure 6. The first spatial patterns of EOF and the first PC time series of mean monthly.

Elevation (km)		< 1.0	[1.0, 1.5)	[1.5, 2.0)	[2.0, 2.5)	[2.5, 3.0)	[3.0, 3.5)	[3.5, 4.0)	[4.0, 4.5)	>= 4.5
Precipitation	Probability	0.00	0.26	0.94	0.96	0.96	0.56	0.77	0.73	0.92
	Trend (mm/year)	-0.10	0.14	3.142	11.02	14.01	-5.23	9.00	7.13	-15.12
Snowfall	Probability	0.77	0.81	0.09	0.42	0.26	0.34	0.34	0.17	0.09
	Trend (mm/year)	-0.07	-0.05	0.00	0.53	1.12	0.24	0.58	0.21	-0.16
Snow water equivalent	Probability	0.81	0.26	0.09	0.90	0.81	0.42	0.09	0.49	0.77
	Trend (kg m-2/year)	-0.01	0.00	0.00	0.06	0.07	-0.01	0.00	-0.03	-0.10
Snow depth	Probability	0.87	0.81	0.00	068	0.68	0.09	0.56	0.87	0.99
	Trend (m/year)	-0.15	-0.07	0.00	0.28	0.45	0.02	-0.20	-0.57	-1.39
Fractional snow cover	Probability	0.62	0.56	0.00	0.77	0.87	0.09	0.42	0.00	0.73
	Trend (%/year)	-0.06	-0.13	-0.01	0.25	0.25	0.05	0.11	0.03	-0.68

Table 1. Probability and trend of precipitation, snowfall, SWE, snow depth and FSC at different altitude ranges.

The effects of climate change on the HRB can be concluded: 1) Due to increases in air temperature, the FSC, snow water equivalent, and snow depth over the whole HRB region have decreased over the past 14 years, especially at elevations above 4,500 m; however, snowfall increased in the mid-altitude ranges over the upstream region of the HRB. 2) Over the upstream region of the HRB, the total snow flux increased; however, the number of snowfall days decreased over the past 14 years. Therefore, extreme snow events may increase over the upstream region of the HRB. 3) The air temperatures in the HRB over the downstream region increased the most; however, the snowfall over this region also decreased over the past 14 years

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