Assessment of the Impact of Climate Change on Snow Distribution and River Flows in a Snow-Dominated Mountainous Watershed in the Western Hindukush–Himalaya, Afghanistan

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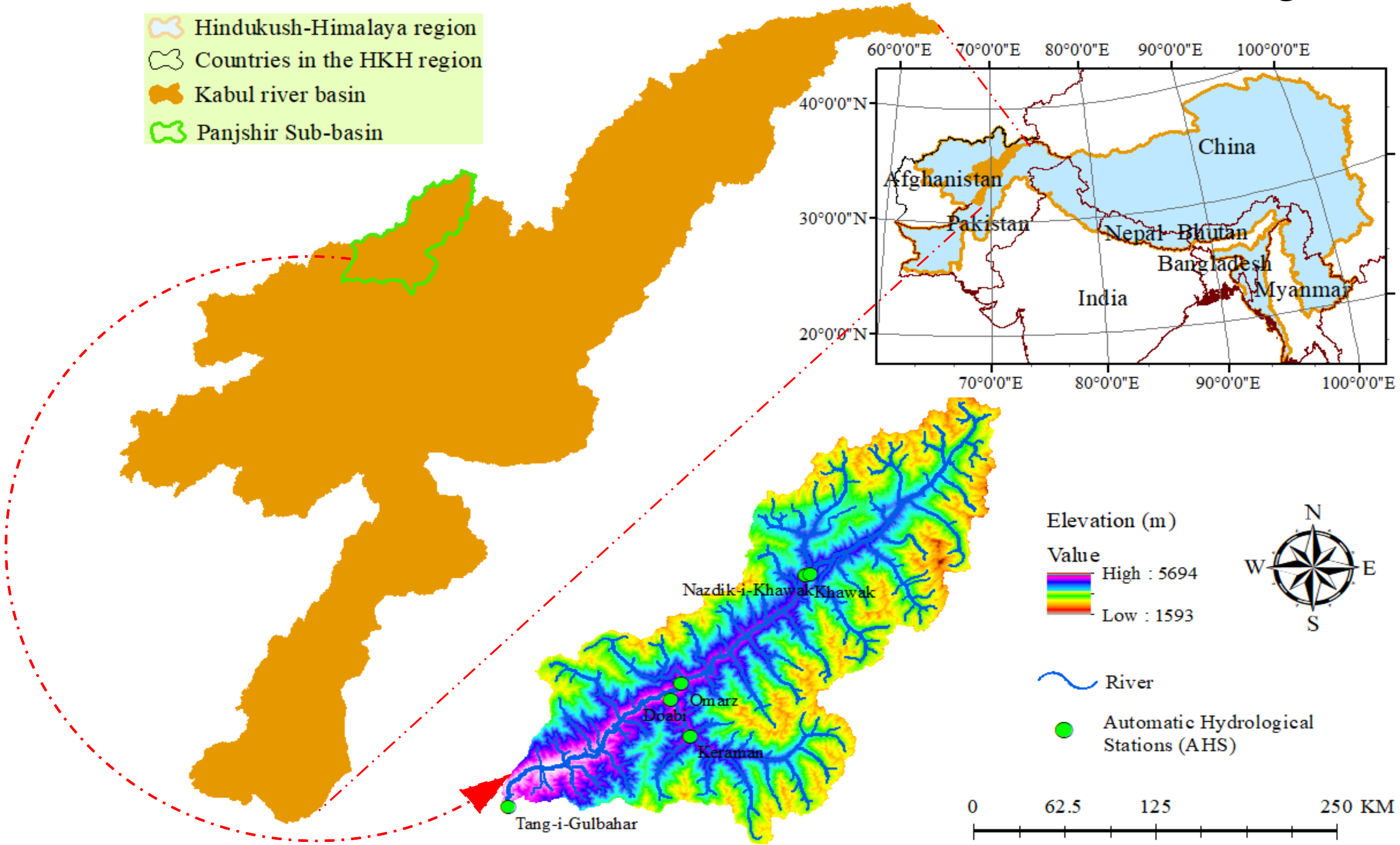
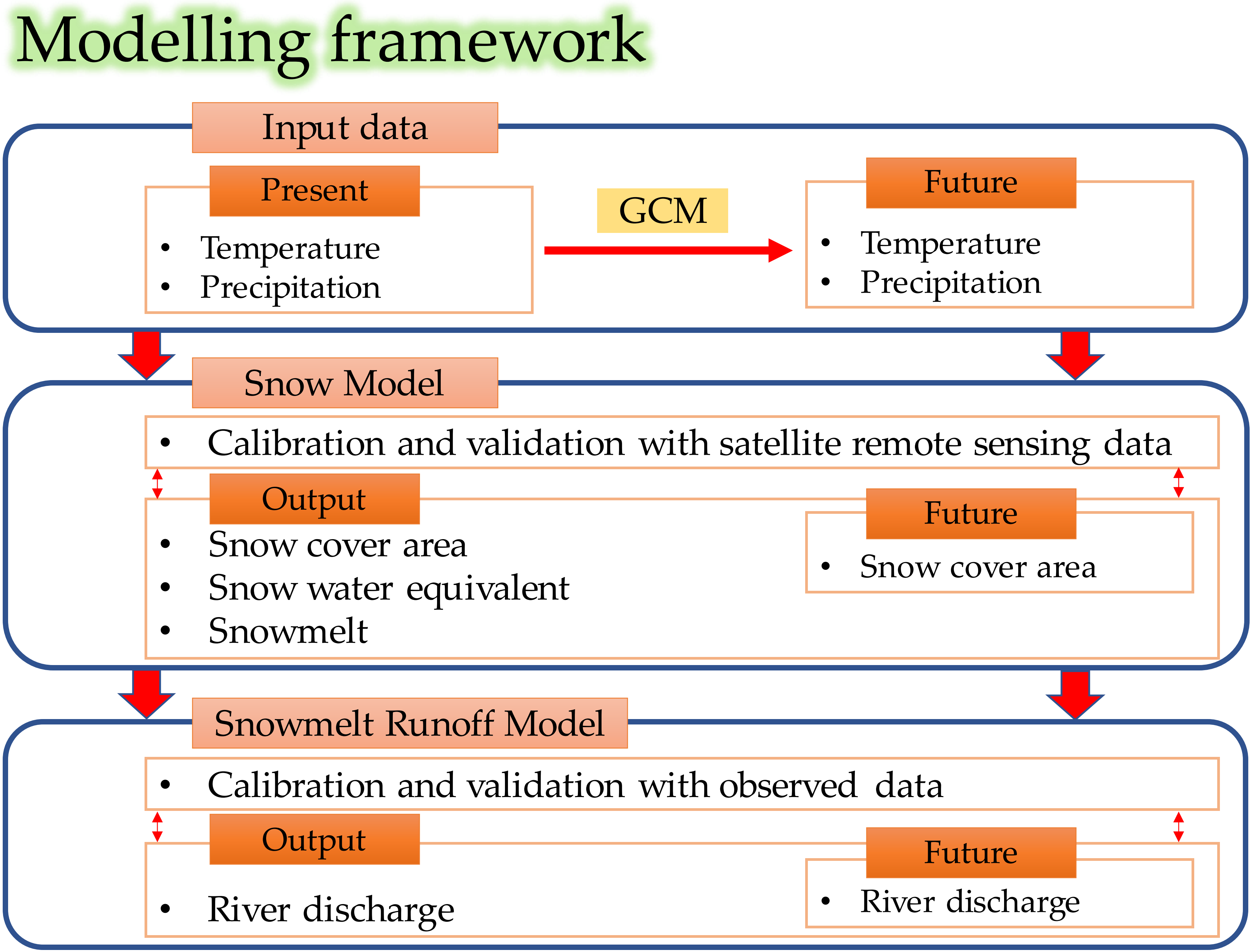
Study area

Map of Panjshir sub-basin including Kabul river basin and HKH region.



- The study area comprises the northeast quarter of Afghanistan, in the Hindukush mountain ranges.
- The sub-basin covers an area of about **3540 km^2**.
- The mean elevation is approximately **3498 (m a.s.l.)**.



Modelling framework
Input data
Present
• Temperature
• Precipitation
GCM
Future
• Temperature
• Precipitation
Snow Model
• Calibration and validation with satellite remote sensing data
Output
• Snow cover area
• Snow water equivalent
• Snowmelt
Future
• Snow cover area
Snowmelt Runoff Model
• Calibration and validation with observed data
Output
• River discharge
Future
• River discharge

Projection of Climate Change scenarios

Id	Model	Resolution	Country
1	CMCC-CM	0.7° x 0.7°	Italy
2	CNRM-CM5	1.4° x 1.4°	France
3	CSRIO-Mk3.6	1.9° x 1.9°	Australia
4	GFDL CM3	2.5° x 2.0°	USA
5	HadGEM2-AO	1.9° x 1.2°	Korea
6	MIROC5	1.4° x 1.4°	Japan
7	MPI-ESM-MR	1.9° x 1.9°	Germany
8	MRI-CGCM3	1.1° x 1.1°	Japan

Delta Change approach:

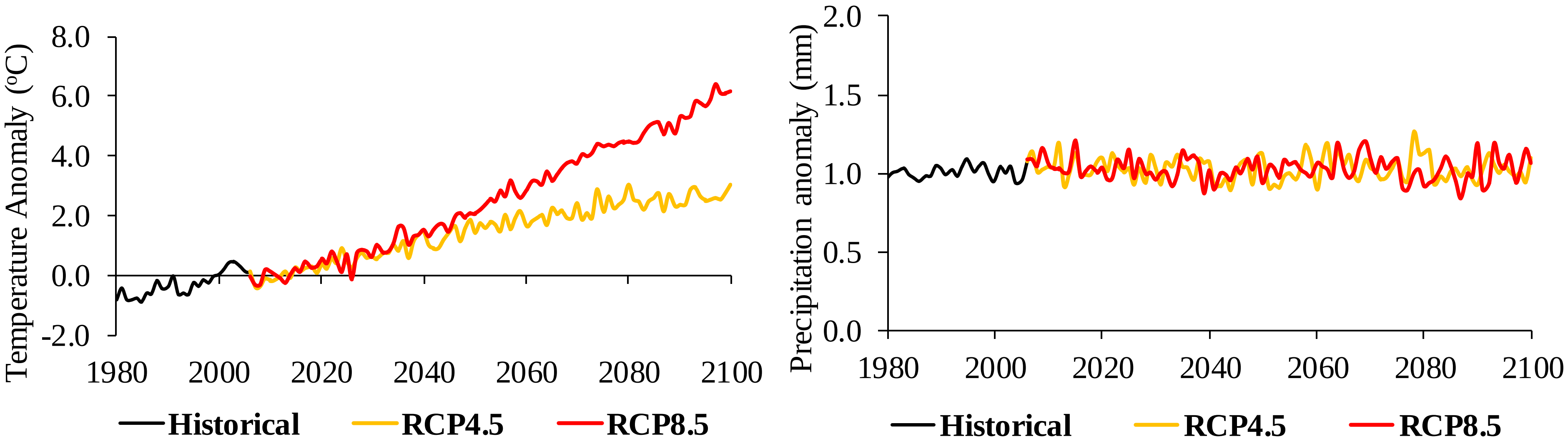
- The future daily precipitation and temperature time series are generated by the following equations:

$$T_{f,daily} = T_{O,daily} + (\overline{T_{f,monthly}} - \overline{T_{p,monthly}})$$

$$P_{f,daily} = P_{O,daily} \frac{\overline{P_{f,monthly}}}{\overline{P_{p,monthly}}}$$

T_f and P_f : Future temperature and precipitation
T_O and P_O: Observed temperature and precipitation
T_p and P_p: Present temperature and precipitation

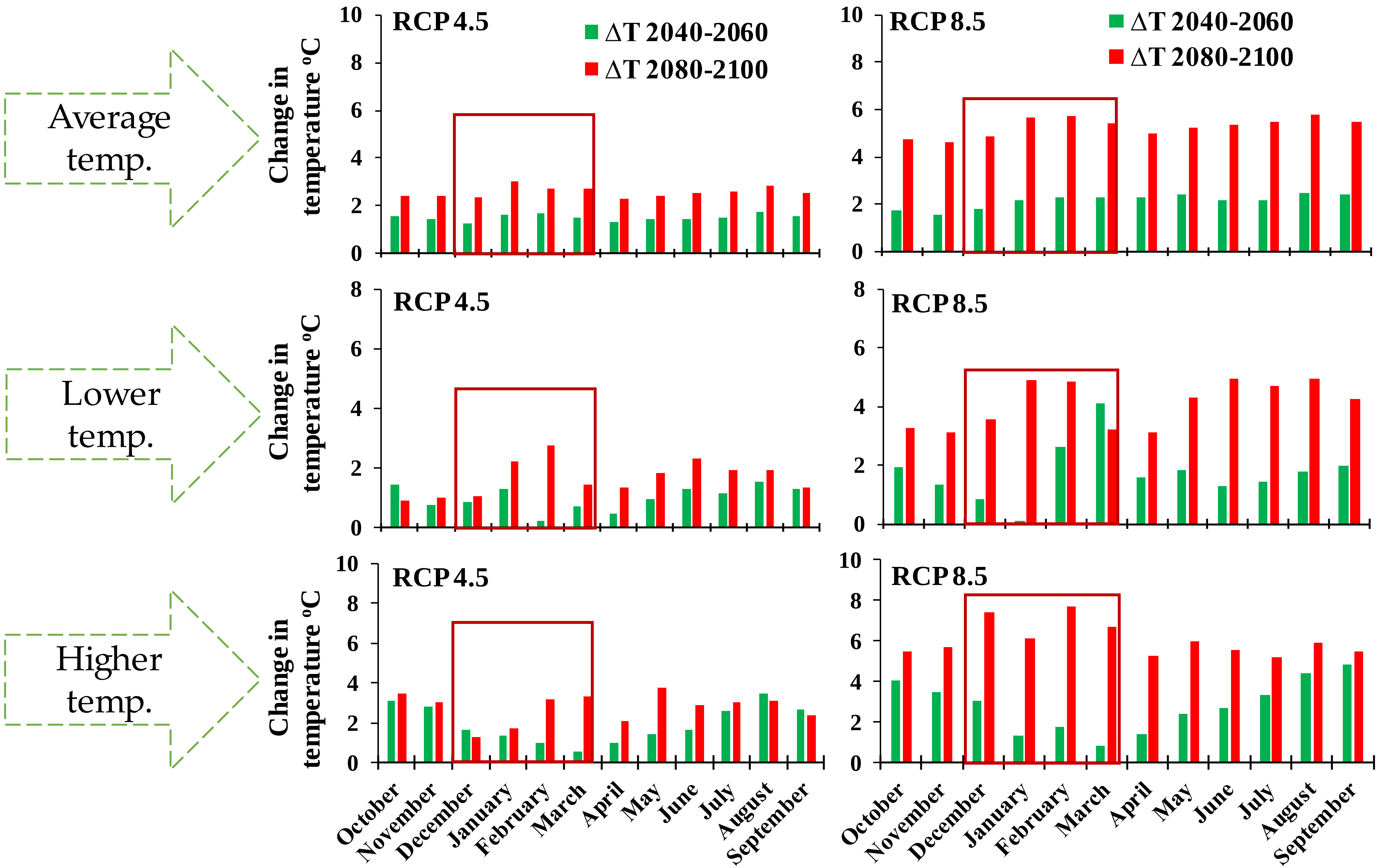
Projection of Climate Change scenarios



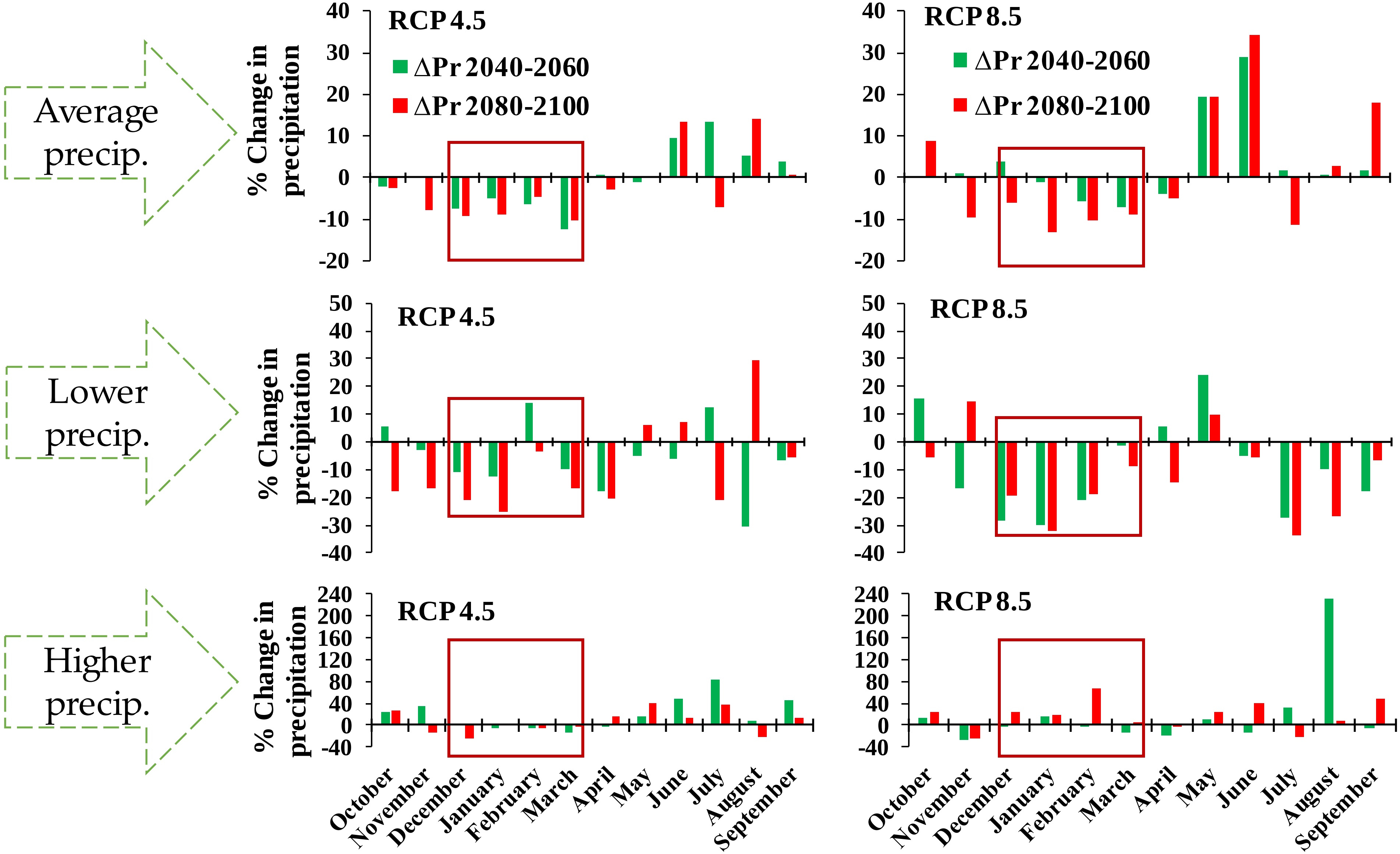
Time Period	RCP Scenarios	Mean annual temperature (°C)	Mean annual precipitation (%)
2040-2060	4.5	+1.45	-4.7
Mid-21st century	8.5	+2.05	-1.7
2080-2100	4.5	+2.51	-5.4
Late-21st century	8.5	+5.20	-4.4

- Mean annual temperature is expected to increase by **+1.45 °C** to **+5.2 °C** under both RCPs during the mid and late-21st century, respectively.
- Meanwhile, precipitation is expected to decrease at a range of **-1.7%** to **-5.4%**.

Monthly changes in temperature



Monthly changes in precipitation



Snow Model (SM)

Snow Model has been used to simulate the distribution of snowfall, SCA, snowmelt, and snow water equivalent spatially and temporally.

$$SWE_{t+1} = SWE_t + (SF_t - SM_t)dt$$

SWE: is the snow water equivalent accumulation in mm
SF: is the daily snowfall at each pixel (mm day^{-1})
SM: is the daily snowmelt rate (mm day^{-1})
t: is the date of snow water equivalent.

$$SM = \begin{cases} \mathbf{DDF}(T_a - T_b), & T_a > T_b \\ 0, & T_a \leq T_b \end{cases}$$

SM: is the daily snowmelt rate (mm day^{-1})
DDF: is the degree-day factor (mm $^{o}C^{-1}$ day^{-1})
T_a : is the mean daily temperature (^{o}C)
T_b : is base temperature

$$P = \left(1 + \boldsymbol{PG}(h - elv_{obs})\right)P_{obs}$$

P: is daily precipitation (mm) at the elevation h (m)
PG: is the precipitation gradient (m^{-1})
Obs: denoting the observation points

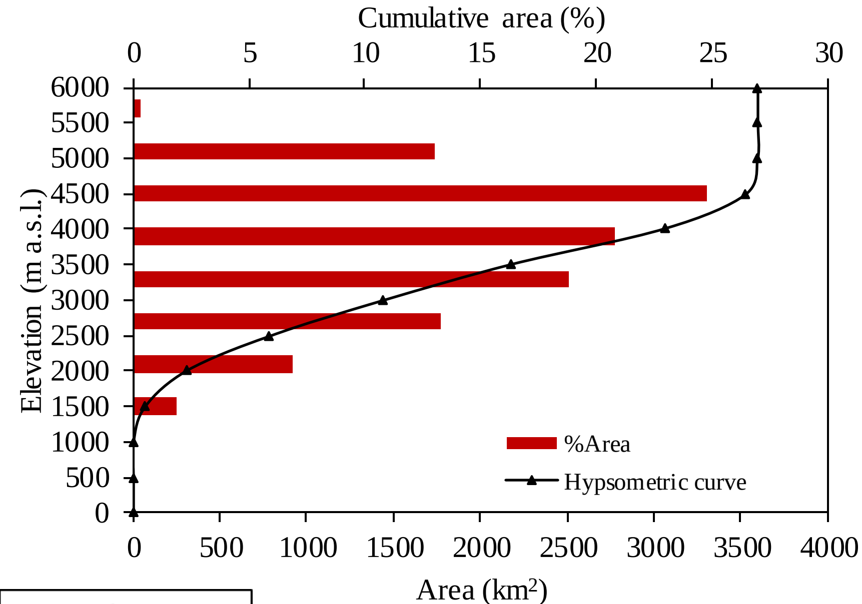
Snowmelt Runoff Model (SRM)

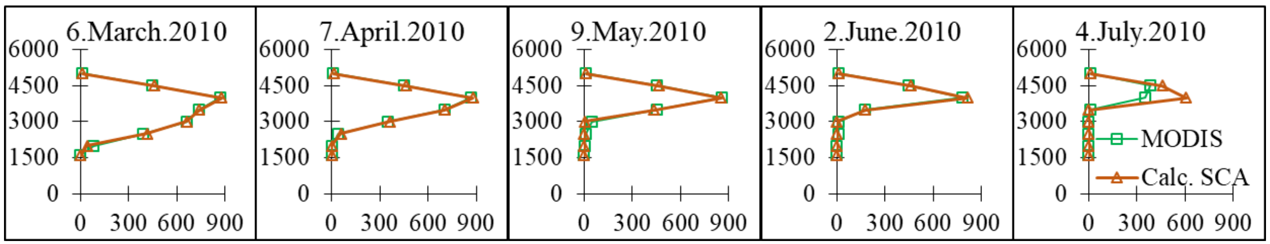
- SRM is improved to simulate and forecast daily flow of the water resulting from snow and glacier melt and rainfall in mountainous environments where snowmelt is the principle contributor to runoff. (Martinec *et al.*, 2008)

$$Q_{n+1} = C_{sn} \cdot a_n (T_n + \Delta T_n) S_n \cdot A \cdot 0.1157 (1 - k_{n+1}) + C_{rn} P_n \cdot A \cdot 0.1157 (1 - k_{n+1}) + (Qs_n + Qr_n) k_{n+1}$$

Q: mean daily discharge ($m^3 s^{-1}$);	***A***: area of basin or zone (km^2);
C_s and C_r: runoff coefficients for snow and rain;	***k***: recession coefficient (X_c and Y_c);
a: degreed-day factor (cm $°C^{-1} d^{-1}$);	***n***: sequence of days during the simulation period.
$T + \Delta T$: are the degree-days (°C d);	The factor of **0.116** converts data from cm $km^2 d^{-1}$ to $m^3 s^{-1}$.
S: ratio of the snow covered area to the total area;	
P: measured precipitation on that day (cm);	

Parameter optimization and calibration





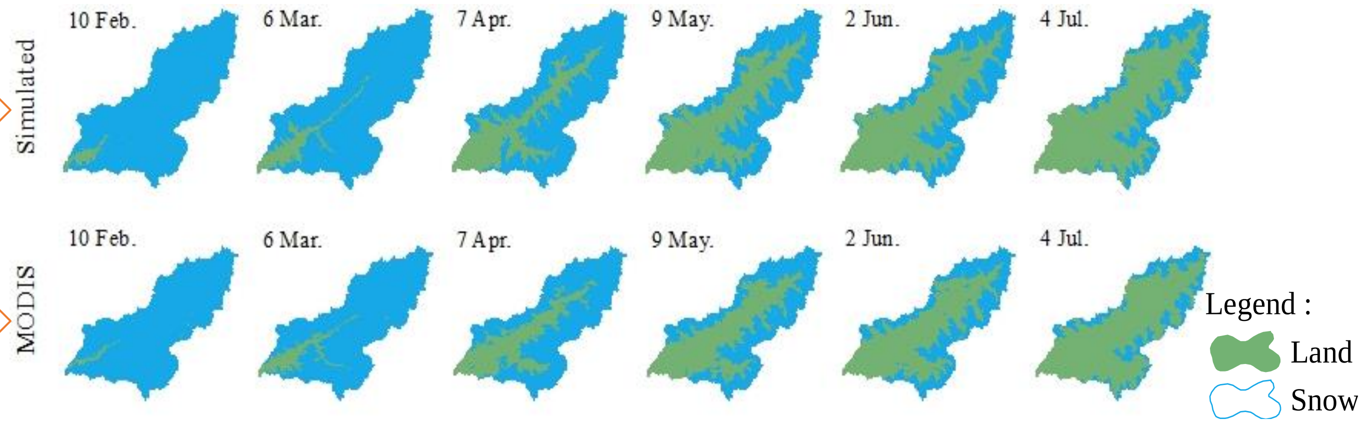
Parameters	Zone A 1593 - 2000	Zone B 2001 - 2500	Zone C 2501 - 3000	Zone D 3001 - 3500	Zone E 3501 - 4000	Zone F 4001 - 4500	Zone G 4501 - 5000	Zone H 5001 - 5694
DDF (cm $^{o}C^{-1}$ d^{-1})	0.3	0.3	0.3	0.6	0.9	0.9	0.9	0.9
Precipitation gradient (m^{-1})	+ 0.002	+ 0.002	+ 0.002	+ 0.002	+ 0.002	0	0	0

- DDF range from 0.3 to 0.9 (cm $^{o}C^{-1}$ d^{-1}) for zones from A to H.
- PG is positive for zone A to E and constant above zone E.

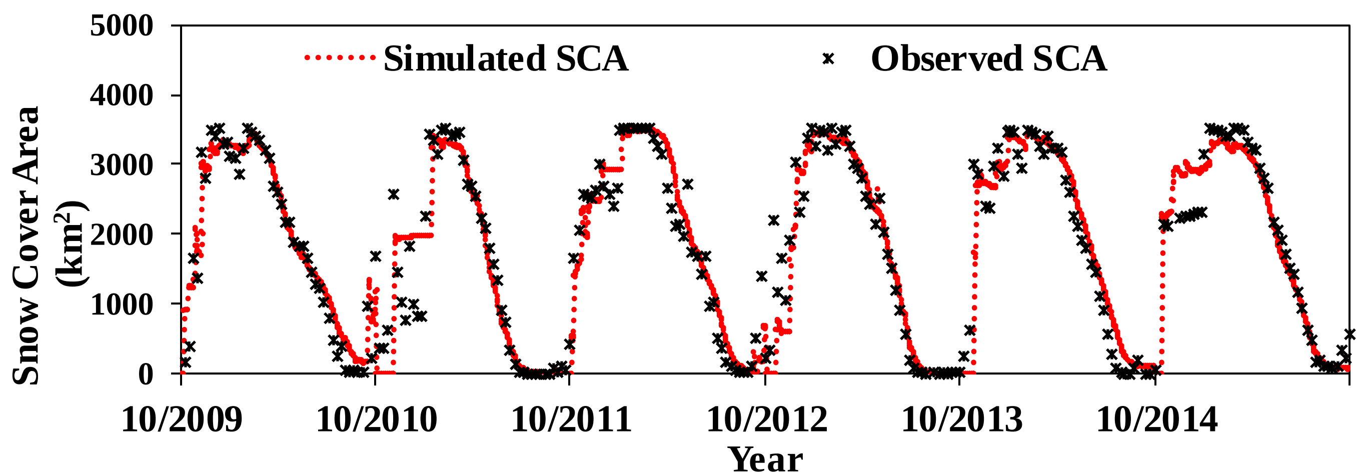
Snow cover simulation

Snow cover simulated by Snow Model

Snow cover observed by Satellite



Evaluation of estimated spatial distribution of SCA with MODIS snow cover data during calibration period 2009-2010.



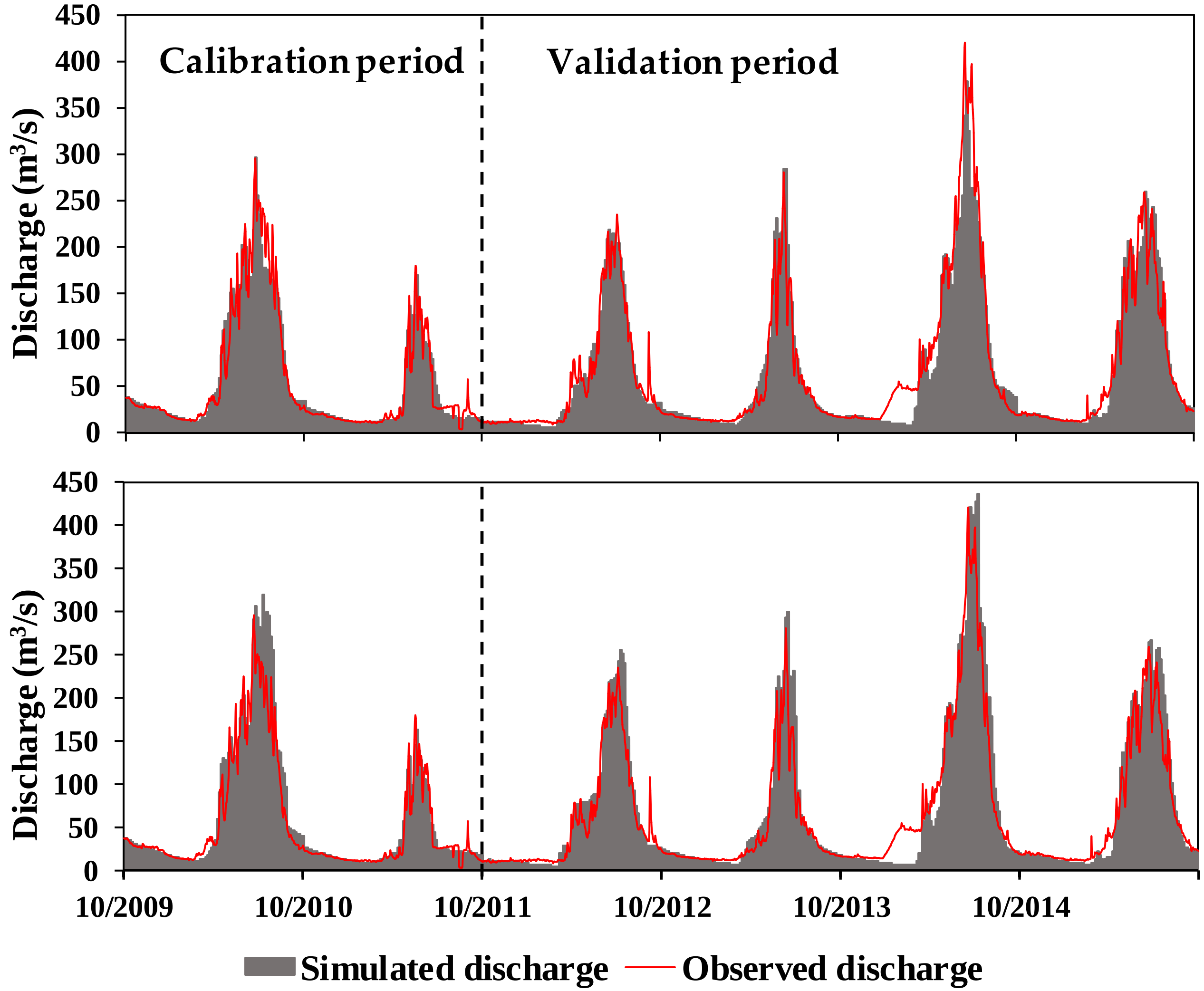
Daily SCA simulated by SM compared with MODIS 8-day interval

Simulated SCA is in good agreement with the SCA obtained from the MODIS 8-day data set with RMSE = 154 km^2.

Runoff simulation

Daily discharge by applying MODIS SCA

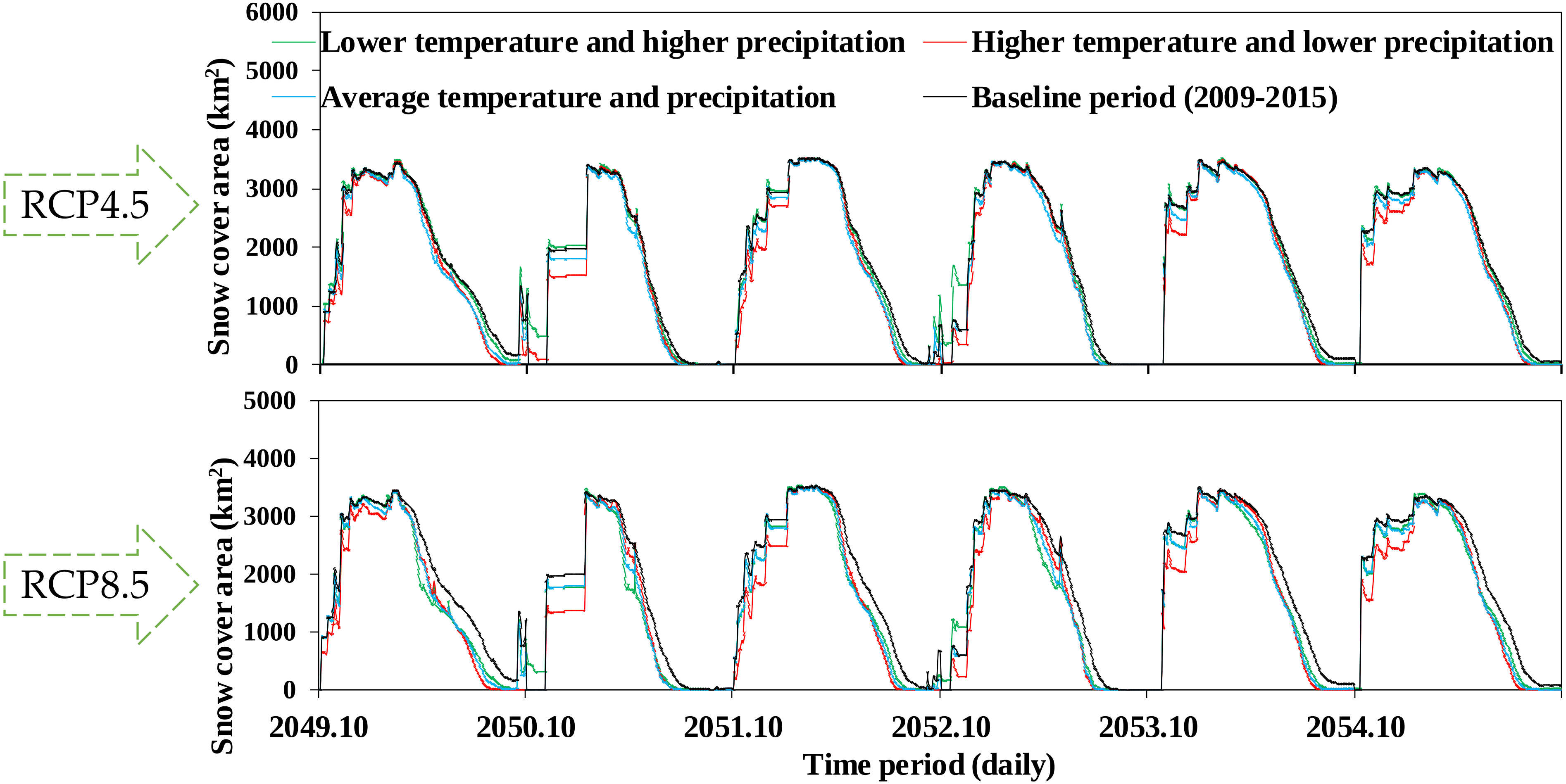
Daily discharge by applying simulated SCA



SRM simulated the river flows efficiently with a minimum efficiency of **0.89** and **0.87** for both the **observed** and **simulated** SCA, respectively.

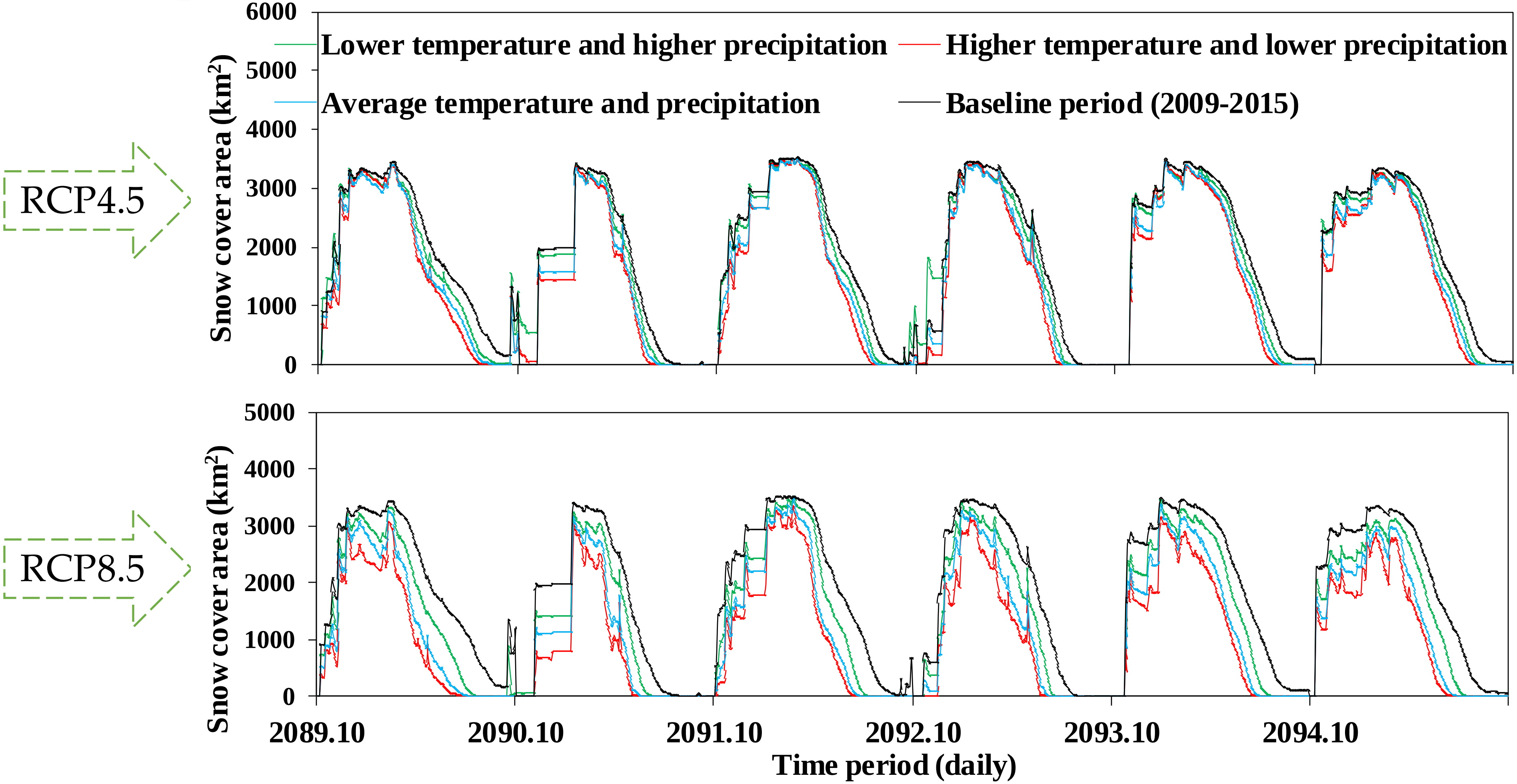
Impact of future climate scenarios:

Projected daily snow cover area during the mid-21st century



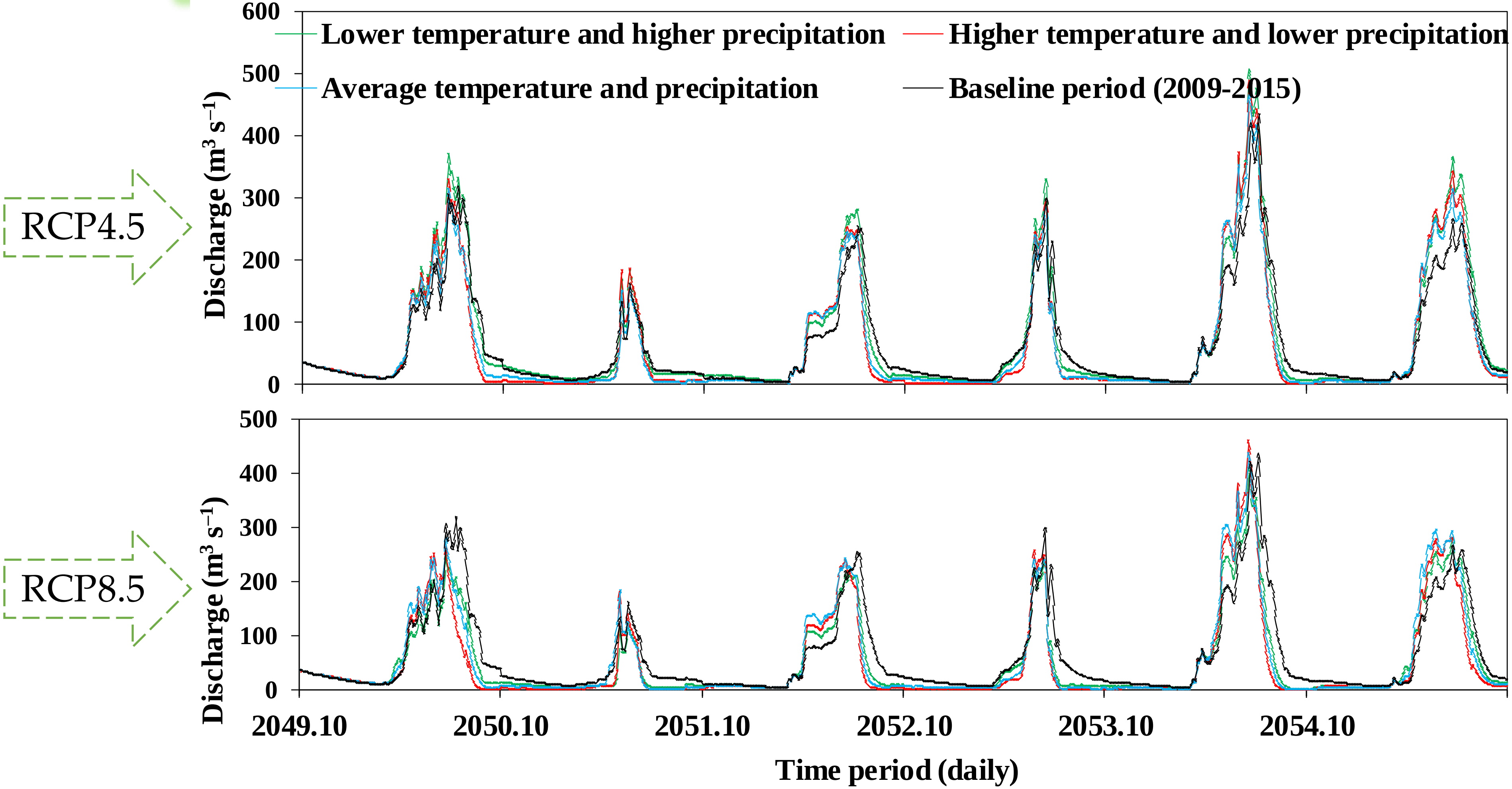
The simulated SCA under projected climate change with regard to **average**, **lower** and **higher** scenarios indicated a decrease of **7%**, **0.15%** and **8%** for **RCP4.5** and **12%**, **10%** and **15%** for **RCP8.5** during mid-21st century, respectively.

Projected daily snow cover area during the late-21st century



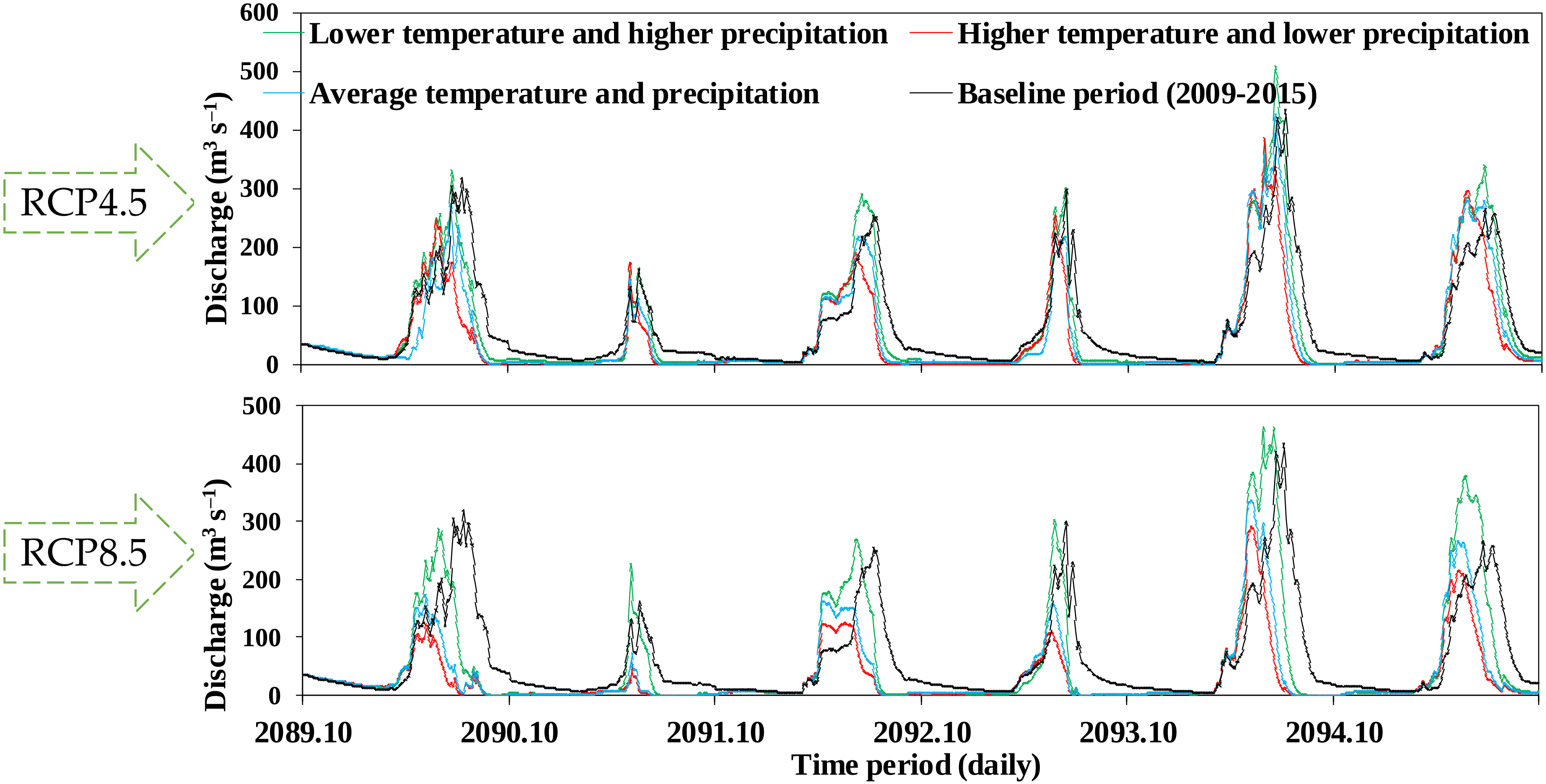
The simulated SCA under projected climate change with regard to **average**, **lower** and **higher** scenarios indicated a decrease of **15%**, **6%** and **19%** for **RCP4.5** and **34%**, **21%** and **44%** for **RCP8.5** during late-21st century, respectively.

Projected daily river discharge during the mid-21st century



The projected runoff also depicted to decreased by **6-7%** for **RCP4.5** and **13-21%** for **RCP8.5**, except for case lower temperature and higher precipitation which suggested an increase of only **9%** in simulated runoff under **RCP4.5** during (2049-2055).

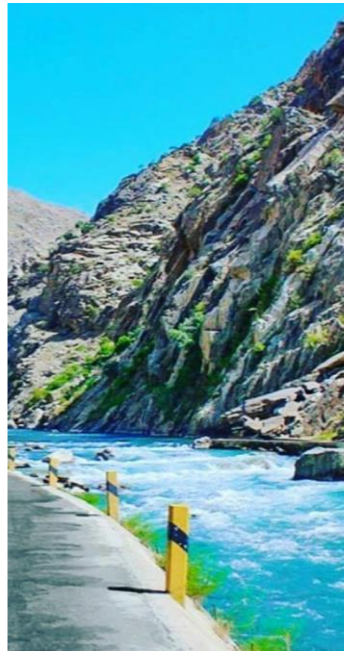
Projected daily river discharge during the late-21st century



The simulated runoff under projected climate change with regard to **average**, **lower** and **higher** scenarios indicated a decrease of **25%**, **7%** and **31%** for **RCP4.5** and **43%**, **13%** and **55%** for **RCP8.5** during late-21st century, respectively.

Conclusion

- In this study, attempts have been made to develop modelling framework to simulate current and future snow cover area and river discharge in the data-scarce snow-dominated basin.
- Changes in future SCA and stream flows will alter the Panjshir sub-basin hydrology and could significantly influence the agriculture irrigation demand, domestic water supply, hydropower generation and ecosystems particularly in the downstream areas which are irrigated.
- Temperature is expected to rise in the future which may alter the hydrological regime of the study area, due to the lack of infrastructure the possibility of severe floods and droughts may contribute to further problems.
- This method can be used to monitor snowmelt runoff for flood forecasting and water resources management of snow-dominated basins in the HKH region.



THANK YOU VERY MUCH FOR YOUR ATTENTION