Chapter 2
Hydrology of the Upper Indus Basin under Changing Climate

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Abstract The recent climate change accelerations intensify future water availability concerns from high-altitude mountainous regions. The Upper Indus Basin (UIB) is a highly snow-fed and glacierized basin from the High Mountains of Asia; thus, an accelerated melt due to climate change may severely affect these frozen water resources. Therefore, increasing knowledge of the future water availability in the Indus Basin under climate scenarios is vital. This research was designed to analyse the future water availability from the Hunza River Basin (sub-basins of the UIB) under the Coupled Model Intercomparison Project Phase 6 (CMIP6) climatic projections. The projected precipitation and temperature from two General Circulation Models (GCMs) were analysed. The Distance Distribution Dynamics (DDD), a data parsimonious rainfall-runoff model was set up using these projections. The simulations were performed for the historical (1991–2010), middle of the century (2041–2060) and end of the century (2081–2100) period under Shared Socioeconomics Pathways (SSP) SSP1, SSP2 and SSP5 emission scenarios. Relative to the baseline temperature, the future projections showed an increase between 1.1 and 8.6 °C based on both GCMs. The 12–32% annual precipitation increase is expected by the end of the twenty-first century, relative to the baseline precipitation. Furthermore, reduced precipitation as snow and increased rainfall are expected together with the changes

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in precipitation cycles. Relative to the baseline glacier melt, a 38–265% glacier melt increase is expected in the river flow. An overall river flow increase of 23–126% is expected by the end of the twenty-first century. This research presented climate change associated future water availability for the study area. Thus, policy-makers and stakeholders could use these findings for reservoir development, modifying hydropower and reservoir development policy, sustainable agriculture, and efficient water resources management.

Keywords CMIP6 · Distance distribution dynamics (DDD) · General circulation models (GCMs) · Hunza basin · Upper Indus basin (UIB)

2.1 Introduction

Due to the unceasing greenhouse gas emissions and global warming, the climate change threat is continuously increasing. Evidence shows climate change impacts are most substantial for natural systems (Masson-Delmotte et al. 2021). The climate change acceleration further intensifies concerns about water availability from mountainous catchments at the pace of climate change (Hasson 2016). This may alter the changing frequency, and quantity of the climatic variables, for instance, precipitation (Hasson 2016). Yet, there are significant uncertainties in the projected and observed climate, particularly precipitation. These uncertainties prevent reliable assessment of the changes and variability at the global and regional scales for current and future water cycles.

The Upper Indus Basin (UIB) exhibited significantly increasing precipitation trends at several stations between 1961 and 1990 (Archer and Fowler 2004). For the same stations, a rise in temperature of 0.76 °C during the last four decades is reported. Akhtar et al. (2008), in their regional climatic modelling using the SRES A2 scenario from PRECIS (2071–2100), projected that by the end of this century, UIB will see a 16% increase in annual mean precipitation and a 4.8 °C rise in temperature. Khattak et al. (2011) reported temperature decline for monsoon and minor warming for winter and spring. Another recent finding concludes that the Shigar River basin (central Karakoram) reported increased flows (Mukhopadhyay and Khan 2014). The authors argued that with temperature and precipitation increase, the glacier's contribution is increasing with the neutral mass balance (Lutz et al. 2016). Bashir et al. (2017) also reported glacier's anomalous behavior of surge with a rise in humidity. However, because of the lack of in-situ data, the complicated terrain, and the local climatic circulations, there are still a lot of unknowns when it comes to accurately reflecting the hydrological and climatic dynamics of the basin. (Lutz et al. 2014; Dahri et al. 2021). The accuracy of future climatic projections is also exposed to variabilities and spread in the outcomes of the general circulation models (GCM) (Lutz et al. 2016). Moreover, these projections have structural limitations in their modelling and reliable observed data is missing for bias corrections and validations.

Hence, significant changes are expected concerning the hydro-climatic regime of the Indus Basin (Dahri et al. 2021).

The novelty of the current study lies in attempting the simulation of the future projections and hydro-climatic regimes by analysing the newly released projections from the Couple Model Intercomparison Project phase 6 (CMIP6) (Eyring et al. 2015) for the Indus basin. Moreover, these projections are forced to a relatively new modelling framework that uses the energy balance (EB) approach for simulating snow and glacier melt. Moreover, as per our knowledge, only a few studies have been conducted on the CMIP6 projections for the UIB. The main objective of this research is to investigate the future runoff regime and water availability under different glacier presence scenarios. The findings of this current study may improve the understanding of the current and future hydro-climatic regime and may provide helpful information concerning future meltwater contributions.

2.2 Data and Methods

2.2.1 Study Area

The Hunza Basin lies in the Karakoram mountains in the HKH region. The total basin area is 13,713 km^2. The basin is starched between 2300 and 7889 masl, with 31% of its entire surface permanently covered by glaciers. Karakoram's frozen freshwater resources are predominantly nourished by the western disturbances (Hasson 2016) (Fig. 2.1). The Hunza basin's precipitation is received with a westerly dominant source (Bookhagen and Burbank 2010). The summer monsoon contributes 27% of the annual precipitation.

2.2.2 Historical Data

The observed runoff was used to calibrate the simulated runoff and GCM historical projections based simulations (1991–2010). The few in-situ gauges in the Hunza basin with a limited record period discourage using this data for such a crucial study (Nazeer et al. 2022). The Hunza basin in the Upper Indus is particularly the most scarcely monitored part. Therefore, in this intricate and orographically impacted high-mountain environment, the current gauges ineffectively measure the precipitation (Dahri et al. 2016). Precipitation estimates by European reanalysis 5 Land gridded dataset developed by the Copernicus Climate Change Service (C3S) were reasonable for the HKH region (Nazeer et al. 2022).

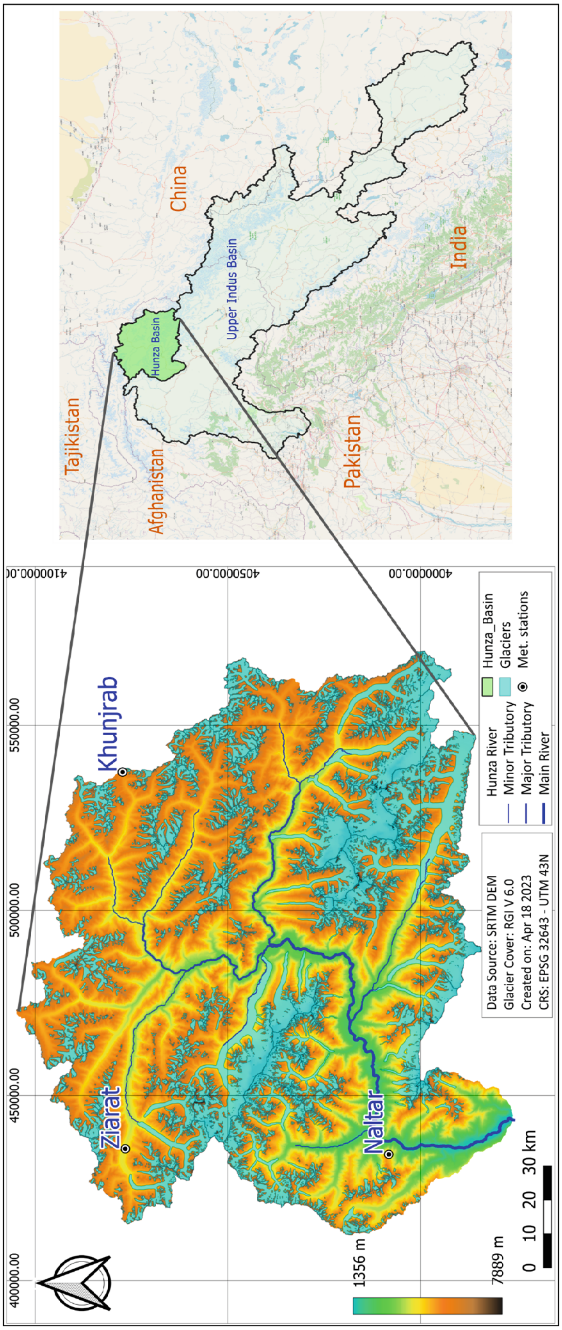

Fig. 2.1 Hunza Basin with glacier cover, river network and meteorological stations

2.2.3 CMIP6 GCM Data

Coupled Models Intercomparison Project Phase 6 (CMIP6) was established by the EC-Earth consortium (Hazeleger et al. 2010; Massonnet et al. 2020). EC-Earth3 with grid size of 0.7° × 0.7° and has global spatial coverage for CMIP6. Because of its comparatively good resolution and performance based on the primary analysis, EC-Earth3 data is chosen for this investigation. The data set is used to derive Hunza's precipitation and temperature from the historical periods of 1991–2010 and respective future periods (2041–2060, and 2081–2100) for Shared Socioeconomic Pathways (SSP) scenarios of SSP1, SSP2 and SSP5. CMIP6 based MPI-ESMI data is used for this study due to its relatively fine resolution and performance based on the primary analysis. The data set is used for temperature and precipitation for the Hunza basin for the historical periods of 1991–2010 and future periods (2041–2060 and 2081–2100) for SSP1, SSP2 and SSP5 scenarios.

2.2.4 Modelling Framework

For this study, the semi-distributed rainfall-runoff Distance Distribution Dynamics (DDD) model was employed. Skaugen and Onof (2014) of the Norwegian Water Resources and Energy Directorate (NVE) derived the model. River flow, SWE, SCA, subsurface water storage, GM, and actual evapotranspiration (ET) are all simulated by the model (Skaugen and Weltzien 2016). The model is data parsimonious and best suited for data-scarce regions having inputs like precipitation and temperature (Nazeer et al. 2021). For data-scarce regions like the Indus, the model is highly reliable for its data parsimonious nature and due to the majority of the model's parameters are not calibrated against runoff but are obtained from digital/GIS maps.

Many uncertainties and model biases affect the accuracy of GCM projections when compared to observed data. Thereby, GCM projections often need bias correction before being applied to future climate and hydrological studies. However, global precipitation products can be good alternatives for such regions' observed data. For the precipitation estimates of data-poor regions, ERA5-Land precipitation is proven as a good alternative (Dahri et al. 2021; Nazeer et al. 2021).

This data, however, overestimates the precipitation and needs correction before applying it as observed data. EAR5-Land precipitation corrected data is an alternative to the Hunza basin's observed data. Hence, three steps of correction include: (i) setting up the model using ERA5-Land and getting the corrected precipitation based on the observed river runoff, (ii) using bias-corrected ERA5 precipitation to bias-correct the elevation-distributed GCM precipitation, and (iii) setting up the model using elevation-distributed bias-corrected GCM's projections. In the model setup using the GCMs projections, the GCMs elevation-distributed, bias-corrected temperature, and precipitation projections are used for the historical period (1991–2010). The model is used in the validation mode. The calibrated parameters are kept similar to those for the observed period simulations.

The accuracy and sound evaluation are assessed using the KGE and NSE efficiency standards. The KGE (Eq. 2.1) is a goodness-of-fit given by KGE (Gupta et al. 2009) is employed for model evaluation, and has applicability negative infinity to 1. On the other hand (Nash and Sutcliffe 1970) (Eq. 2.2) assess the relative magnitude of variance compared with the variance in observed data and subtracted from unity.

$$KGE = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_{sim}}{up\sigma_{obs}} - 1\right)^2 + \left(\frac{\mu_{sim}}{\mu_{obs}} - 1\right)^2} \tag{2.1}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{obsi} - Q_{simi})^2}{\sum_{i=1}^{n}\left(Q_{obsi} - \overline{Q_{obs}}\right)^2} \tag{2.2}$$

where r, σ, μ and Q show the linear correlation, standard deviation, mean, and flow, respectively. Subscripts *obs* and *sim* show the observed and simulated data, respectively.

2.3 Results

2.3.1 Historical Simulations

In the first modelling setup, the runoff was simulated using ERA5-Land based precipitation on calibration (1997–2005) and validation (2006–2010) for the Basin. The station temperature data were used as model input. For the higher elevations, the highest station (4730 masl) data was used as a reference together with the temperature lapse rate derived from the APHRODITE data. The slightly revised subroutine to simulate glacier melt changed the results, but these changes are less significant and discussed later.

The ECE3 based simulation showed KGE as 0.80 and NSE as 0.74, with an overestimated runoff of 5.1%. In comparison, the ESMI based simulation showed KGE as 0.83 and NSE as 0.77, with a slightly overestimated runoff of 8.1%. With the increase in temperature in April, the runoff starts increasing, initially due to the snowmelt from lower elevations. The sharp rise and decline in temperature generate immediate snowmelt. The observed runoff of the Hunza River indicates short-term multiple flow peaks. The GCM data simulated similar multiple peaks but could not reproduce all of them and the flow peaks due to flooding in the river (for instance, 1994 and 2010). The ESMI based GCM simulation performed relatively better in this regard. There is a slight increasing trend in runoff from 1991 to 2010, both in modelled and gauged flow for the basin.

The ECE3 based 1991–2010 simulation showed the maximum basin-scale yearly SCA as 70.3% for 1992 and at least 60.2% in 1996, with 63.7% for the Hunza basin. The ESMI simulation showed its maximum as 70.5% for 1994, least as 59.4%, with an average of 63.6%. These SCA estimates agree with MODIS data (Muhammad et al. 2019), showing 60% (average) area under snow with an average of 233 mm per year, the ECE3-based SWE displayed a maximum of 278 mm in 2007 and a minimum of 174 mm in 2010. By contrast, the simulation based on ECE3 revealed a minimum of 174 mm in 2010 and a high of 337 mm in 1993.

The observed data-based simulations and elevation-distributed estimations are in agreement where the lowest elevations are the least snow-covered, while the higher altitudes are primarily under snow for the year. Both observed and GCM-based simulations indicate that 14–17% area of the lowest elevation (a1) is covered with snow on an annual mean scale. While the highest altitude (a10) is 97–100% covered with snow. The SWE is least simulated (6 mm) from a1 and maximum (43–45 mm) simulated from GCM-based simulations.

The glacier melt simulations are shown in Fig. 2.2. Using two GCM inputs and an energy balance technique, the DDD model simulates the melting of glaciers. The maximum annual glacier melt is simulated as 620 mm for 2008 and 679 mm for 2007, the minimum as 288 mm for 1995 and 351 mm for 1994, respectively, based on ECE3 and ESMI inputs. The annual mean glacier melt) is projected as 512 mm from ECE3 based simulations and 553 mm from ESMI based simulations. The glacier melt shows a slightly increasing trend from 1991 to 2010. Based on GCM and observed data simulations, the lowest elevation with less than 2% of total glacier cover contributes 28–29 mm of water. At the same time, the highest elevation, with about 27% of the total glacier melt, contributes 1–13 mm. Because of the higher temperature in lower elevations, more melt is generated and vice versa for higher elevations. The elevation zone a9 generates the maximum melt, followed by a8 and a2.

2.3.2 Future Simulations

The GCM based bias-corrected temperature estimates for the Hunza basin are discussed in this section. Results further show a comparison with respective GCM's bias-corrected historical temperatures. Based on all scenarios, the mean monthly temperature increase is slightly higher in ECE3 GCM than ESMI. This future temperature increases from historical end-century periods and from year to year within twenty years of these periods.

The mean annual basin's temperature indicates all 20 years of the historical period below 0 °C in both GCMs. The SSP1 indicates a slight temperature rise for the mid-century period but then a temperature drops. ECE3 indicates a mean annual temperature below 0 °C for a few years for mid-century, but the temperature is closer to 0 °C. In comparison, ESMI indicates below 0 °C for all years of the mid-century period. ECE3's SSP2 indicates only a few years with a temperature below 0 °C than

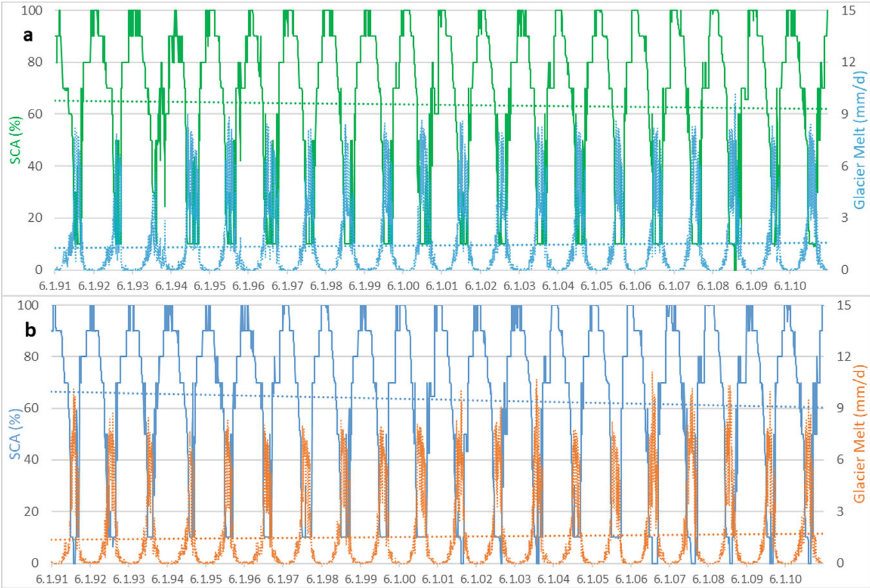

Fig. 2.2 Time series of daily snow cover area (SCA) and glacier melt using **a** ECE3 **b** ESMI GCM

ESMI's SSP2, showing more years with a temperature above 0 °C. For SSP5, both GCMs indicate temperatures above 0 °C for all years of the end-century period. The basin-scale annual temperature averaged for all 20 years of the historical period indicates around − 3 °C for both GCMs.

Relative to the historical period, the annual precipitation seems to increase for all selected scenarios for both GCMs. The post-monsoon receives the least precipitation in the basin. These monthly estimates for historical periods are similar. The GCM's monthly changes in precipitation relative to their respective historical periods are shown in Table 2.1. The precipitations are increasing annually, but data shows uncertain monthly precipitation changes relative to the historical period. For ECE3 data, the maximum increase in precipitation is expected in May for all scenarios, and reduced precipitation is expected in April. The maximum precipitation increase could be 133% for May for SSP2-end-century followed by 130% for June for SSP5-end-century, and the maximum decrease could be 26% for April followed by 19% for December for SSP5-end century.

The ECE3 based historical estimates indicate a minimum annual precipitation of 312 mm for 2010 and a maximum of 498 mm for 2007, with an annual mean of 428 mm. For mid-century, ECE3 indicated the minimum annual precipitation of 407 mm for 2057 and a maximum of 760 mm for 2059 in SSP5. The mean annual precipitation is estimated at 509, 508 and 541 mm for the mid-century period for SSP1, SSP2, and SSP5 scenarios, respectively. For the end-century, ECE3 indicated the minimum annual precipitation of 323 mm for 2088 and a maximum of 773 mm for 2094 for SSP5. For the end-century period, the mean annual precipitation is

Table 2.1 Changes in monthly (mean value) precipitation (%) versus historical data

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ECE3-Baseline (mm)		*44*	*48*	*34*	*30*	*18*	*21*	*30*	*35*	*27*	*9*	*11*	*35*
ECE3 - SSP1	mid-century	18	18	16	-15	74	16	56	30	-11	12	41	6
	end-century	35	15	16	23	90	-10	20	12	27	7	74	11
	Avg	26	17	16	4	82	3	38	21	8	9	58	8
ECE3 - SSP2	mid-century	8	15	22	5	88	3	28	5	3	26	44	4
	end-century	27	17	18	-11	133	17	13	3	-1	21	89	10
	Avg	17	16	20	-3	111	10	21	4	1	24	66	7
ECE3 - SSP5	mid-century	58	9	22	-9	111	11	58	-4	15	38	17	26
	end-century	31	43	8	-26	96	130	59	-14	25	120	-8	-19
	Avg	45	26	15	-17	103	70	59	-9	20	79	4	3
ESMI-Baseline (mm)		*45*	*52*	*36*	*31*	*17*	*20*	*29*	*33*	*24*	*10*	*12*	*36*
ESMI - SSP1	mid-century	32	18	19	4	13	-6	59	31	-8	38	43	32
	end-century	18	25	1	6	-7	-21	13	-30	-10	41	78	23
	Avg	25	22	10	5	3	-13	36	0	-9	40	61	28
ESMI - SSP2	mid-century	42	5	13	4	8	-27	43	-29	-45	14	27	25
	end-century	40	6	7	-6	23	-16	22	-12	-11	52	37	15
	Avg	41	5	10	-1	15	-22	32	-21	-28	33	32	20
ESMI - SSP5	mid-century	15	2	4	-12	24	0	36	9	5	19	66	14
	end-century	28	29	-1	-20	80	-32	16	-62	-47	21	61	40
	Avg	21	15	1	-16	52	-16	26	-27	-21	20	64	27

estimated at 539, 530, and 562 mm for SSP1, SSP2 and SSP5 scenarios. The ESMI based historical estimates indicate a minimum annual precipitation of 318 mm for 2002 and a maximum of 567 mm for 1993, with an annual mean of 427 mm. For mid-century, ESMI indicated the minimum annual precipitation of 303 mm for 2057 for SSP2 and a maximum of 775 mm for 2053 for SSP1. The mean annual precipitation is 547, 479, and 493 mm for the mid-century SSP1, SSP2 and SSP5 scenarios. For the end-century, ESMI indicated the minimum annual precipitation of 303 mm for 2082 and a maximum of 694 mm for 2094 for SSP1.

2.3.3 Future Runoff and Water Availability

This section presents future runoff simulations based on GCMs and all selected scenarios. Runoff determined by past forecasts is also contrasted with future runoff based on GCM. The future runoff simulations are further presented in the following section under three different glacier presence scenarios of the Hunza basin. The whole glacier cover is considered intact (100% present) for all selected scenarios in this scenario. The simulated runoffs under different scenarios are compared with historical data-driven runoff and intact glaciers. The runoff with intact glacier scenario is increased compared with historical simulated runoff for all scenarios of both future periods. The runoff increases from year to year within twenty years of these periods and from historical to future periods.

The ECE3-based simulation for the historical period showed a minimum monthly flow of 24 m^3/sec for February and a maximum of 836 m^3/s for July, with a mean of 306 m^3/s. The ECE3-based mid-century period has the minimum mean monthly flow of 51 m^3/s for February for SSP2 and a maximum of 1080 m^3/s for July for SSP1. In comparison, ECE3 based end-century period has the minimum mean monthly flow of 60 m^3/s for SSP1 for Jan and a maximum of 1092 m^3/sec for July for SSP5. The ESMI-based simulation for the historical period showed a minimum mean monthly flow of 20 m^3/sec for February and a maximum of 917 m^3/sec for August, with a mean of 315 m^3/sec. The mid-century period showed the minimum mean monthly flow of 40 m^3/sec in February for SSP5 and a maximum of 1194 m^3/sec in July for SSP1.

In the glaciers reduced to elevation above 4000 masl scenarios, the mean monthly simulated runoff ECE3 based inputs are shown in Fig. 2.3. The simulated runoffs are compared with historical data driven runoff with reduced glacier cover. However, the runoff using the same inputs and scenarios with reduced glacier cover is reduced than with intact glacier scenarios. But it is still higher than the runoff simulated using historical data from the respective GCMS for future periods and all scenarios. The runoff increases from year to year within twenty years of these periods and from historical to mid-century to end-century periods.

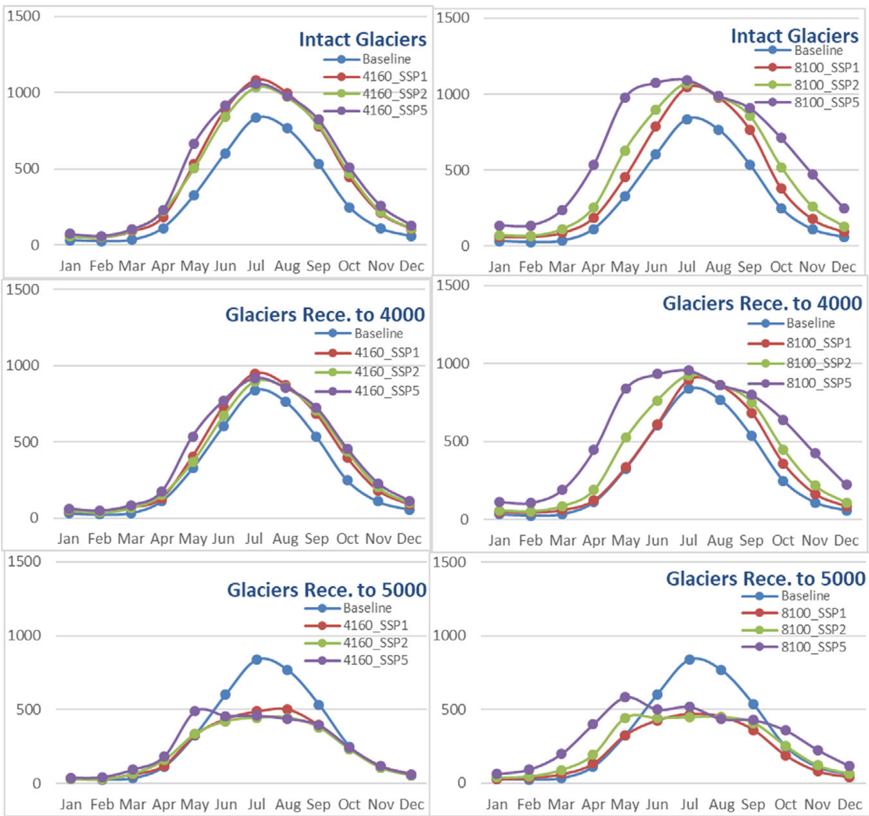

Fig. 2.3 Mean monthly simulated runoff for future periods vs historical period using ECE3 GCM

In this scenario, the glaciers are reduced to elevation above 5000 for all selected scenarios of future periods. The mean monthly simulated runoff with further reduced glacier cover and ESM based inputs are shown in Fig. 2.4. The simulated runoffs are compared with historical data-driven runoff, reducing glacier cover. There is a significant reduction in runoff relative to the historical runoff. Also, runoff is significantly reduced compared with the runoff produced with glacier presence scenarios 1 and 2. These runoff reduction patterns with further reduced glacier cover are consistent for all selected scenarios of both GCMs. The elevation-distributed least melting contributions difference is observed in the lowest elevation, with more differences relative to the historical period melt. The least melting difference could be 2–3 mm for the lowest elevation (a1) for all scenarios for both future periods.

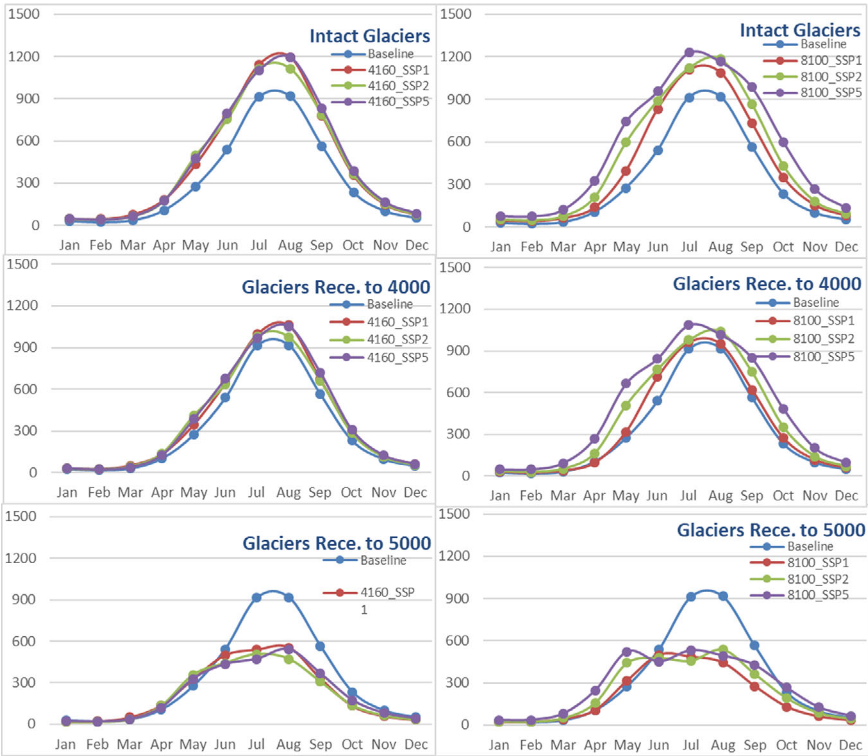

Fig. 2.4 Mean monthly simulated runoff for future periods vs historical period using ESMI GCM

2.4 Discussions

Temperature is the primary indicator of sensitive climate change indicators with significant impacts on the basin's hydrology. The CMIP6 GCM of ECE3 and ESMI-based scenarios for SSP1, SSP2, and SSP5 indicate a highly uncertain future climate for the Hunza basin. But all scenarios based on both GCMs show that the future will warm, with the end-of-century SSP5 scenario showing a more significant warming. A temperature above 0 °C may significantly affect the hydroclimatic regime and runoff dynamics. A temperature of about 0 °C is a threshold for snow or rain. So, this higher temperature immediately may change the precipitation dynamics with more rain than snow. This will ultimately influence the runoff regime as more rainfalls will generate more direct runoff, and less snow will be stored. The year-to-year increase is also associated with year-to-year temperature increases. The temperature rise in all future scenarios is evident. Elevation-distributed glaciers in the Hunza basin and mean annual future glacier melt are presented in Table 2.2. The melt dependent Hunza basin has proved to be very sensitive to temperature. Consequently, higher year-to-year and overall will produce higher runoff because of more melt contribution.

The increased future runoff is primarily associated with a surge in precipitation and temperature. The increased precipitation will generate direct river runoff if it falls as rainfall. Assume that the precipitation falls in the form of snow. Due to temperature rise in future periods, precipitation as rainfall will be increased than snow. This will generate more base flow, and the stored snow will start melting earlier than it melts. So, significant changes are likely in the base flow regime with

Table 2.2 Future glaciers melt from different elevations in the Hunza basin

		GM1	GM2	GM3	GM4	GM5	GM6	GM7	GM8	GM9	GM10
Glacier cover (%)		*1.6*	*4.7*	*5.4*	*6.0*	*6.8*	*8.1*	*10.2*	*13.4*	*17.2*	*26.7*
ECE3 Baseline (mm)		*29*	*67*	*65*	*54*	*51*	*50*	*56*	*66*	*73*	*1*
ECE3 -	mid-century	31	99	75	65	67	72	85	107	126	107
SSP1	end-century	31	97	72	61	60	62	72	89	101	67
(mm)	**Avg**	31	98	73	63	63	67	79	98	114	87
ECE3 -	mid-century	32	100	77	66	67	71	86	106	124	93
SSP2	end-century	33	103	80	72	72	78	92	118	137	128
(mm)	**Avg**	33	101	78	69	70	74	89	112	130	110
ECE3 -	mid-century	32	100	77	69	71	77	92	118	139	115
SSP5	end-century	36	119	95	89	93	104	125	165	200	254
(mm)	**Avg**	34	110	86	79	82	90	109	141	170	184
ESMI Baseline (mm)		*28*	*66*	*65*	*55*	*53*	*53*	*61*	*74*	*84*	*13*
ECE3 -	mid-century	31	94	74	63	62	67	80	97	114	56
SSP1	end-century	32	94	75	65	66	70	83	101	118	60
(mm)	**Avg**	32	94	75	64	64	68	82	99	116	58
ECE3 -	mid-century	32	95	77	68	70	72	87	108	127	81
SSP2	end-century	33	98	81	72	75	81	98	124	146	120
(mm)	**Avg**	33	96	79	70	72	77	93	116	136	100
ECE3 -	mid-century	32	95	78	69	70	75	88	110	130	92
SSP5	end-century	36	108	93	87	90	98	120	152	186	205
(mm)	**Avg**	34	102	86	78	80	86	104	131	158	148

more runoff and reduced base flow duration. The increased temperature will increase the energy available and, ultimately, the accelerated melt process. The increased melt contributions will increase the river runoff.

The hydrological regimes and processes in the HKH region are complex and challenging to investigate, so the underestimated runoff peaks are reported in the previous investigations. Tahir et al. (2011) for the Hunza Basin simulated underestimated peak flows and suggested the precipitation input is responsible. The changes in different hydrological components for scenarios and both GCMS are presented in Table 2.3. These changes are presented as percentages relative to the historical period in all components. The Hunza's mean runoff for the intact glaciers scenario is expected to increase between 31 and 126%. The Hunza's mean simulated runoff for glaciers presence scenario two is expected to increase for mid-century between 15–62% and 29–66%, and end-century between 14–109% and 18–119% for ECE3 and ESMI based simulations, respectively. The runoff for the glacier presence third scenario is expected to be reduced significantly relative to the historical period with intact glaciers and the second glacier presence scenario, except for ECE3 based SSP5-end-century. The runoff is expected to decrease for mid-century between 11–26% and 20–39%, and for end-century, between 10–26% and 14–40% for ECE3 and ESMI based simulations. For ECE3 based SSP5-end-century simulations, there could be a slight increase (14–27%).

The glacier melt is likely to increase for all scenarios for both GCMs. The Hunza's mean glacier melt for intact glaciers scenario is expected to increase between 53 and 265% for ECE3 based simulations. For ESMI based simulations, this glacier melt is expected to surge between 38 and 172%. The glacier melt also increases for

Table 2.3 Percentage variations in the future water availability under all future climate change scenarios relative to the historical period

Runoff comp.	SSP's	mid-century intact glaciers			end-century intact glaciers			mid-century glac. recession to 4000 m			end-century glac. recession to 5000 m			mid-century glac. recession to 4000 m			end-century glac. recession to 5000 m		
		Min	*Max*	*Median*	*Min*	*Max*	*Median*	*Min*	*Max*	*Median*	*Min*	*Max*	*Median*	*Min*	*Max*	*Median*	*Min*	*Max*	*Median*
Qsim - ECE3	**SSP1**	72	39	47	63	31	38	45	21	25	33	14	16	-11	-26	-24	-22	-26	-23
	SSP2	73	34	46	84	58	59	43	15	24	49	37	35	-17	-27	-22	-21	-10	-19
	SSP5	93	48	58	126	95	104	62	29	35	109	73	77	-11	-18	-15	27	14	7
Glacier melt - ECE3	**SSP1**	140	63	63	92	53	39	87	41	33	11	30	10	-16	-25	-21	-71	-33	-48
	SSP2	86	70	61	149	75	78	37	41	31	96	50	48	-49	-31	-35	-21	-11	-16
	SSP5	141	66	74	265	172	150	88	39	44	204	141	115	-35	-19	-25	60	51	23
Rainfall - ECE3	**SSP1**	64	58	49	103	43	40	64	58	49	103	43	40	64	58	49	103	43	40
	SSP2	39	52	46	87	62	54	39	52	46	87	62	54	39	52	46	87	62	54
	SSP5	81	47	59	154	101	117	81	47	59	154	101	117	81	47	59	154	101	117
Snowmelt - ECE3	**SSP1**	1	16	2	-1	35	14	1	16	2	-1	35	14	1	16	2	-1	35	14
	SSP2	-25	17	0	-18	25	1	-25	17	0	-18	25	1	-25	17	0	-18	25	1
	SSP5	-28	25	8	23	22	-24	-28	25	8	23	22	-24	-28	25	8	23	22	21
ET - ECE3	**SSP1**	61	30	35	27	28	22	59	29	33	25	25	18	51	22	27	24	24	18
	SSP2	45	37	35	70	39	44	43	33	31	69	39	43	43	31	29	58	35	39
	SSP5	65	39	42	120	96	86	66	36	40	119	94	84	62	33	37	115	91	81
Qsim - ESMI	**SSP1**	50	34	39	49	23	33	-31	-20	-28	-40	-27	-35	-31	-20	-28	-40	-27	-35
	SSP2	49	40	38	69	43	53	-39	-29	-33	-29	-24	-24	-39	-29	-33	-29	-24	-24
	SSP5	62	30	43	99	60	78	-36	-28	-30	-14	-17	-13	-36	-28	-30	-14	-17	-13
Glacier melt - ESMI	**SSP1**	38	38	34	64	42	38	-2	17	8	28	20	12	-71	-38	-50	-55	-39	-47
	SSP2	48	72	48	110	62	68	7	51	21	62	37	40	-68	-18	-41	-26	-28	-27
	SSP5	110	47	52	172	104	112	67	23	25	128	75	82	-24	-34	-38	28	-1	0
Rainfall - ESMI	**SSP1**	26	30	21	-1	17	17	26	30	21	-1	17	17	26	30	21	-1	17	17
	SSP2	15	15	14	-31	18	9	15	15	14	-31	18	9	15	15	14	-31	18	9
	SSP5	1	9	5	-10	35	3	1	9	5	-10	35	3	1	9	5	-10	35	3
Snowmelt - ESMI	**SSP1**	35	32	27	34	-22	-6	35	32	27	34	-22	-6	35	32	27	34	-22	-6
	SSP2	-50	3	-1	35	1	15	-50	3	-1	35	1	15	-50	3	-1	35	1	15
	SSP5	22	43	26	71	-8	18	22	43	26	71	-8	18	22	43	26	71	-8	18
ET - ESMI	**SSP1**	27	15	15	37	13	17	26	14	14	40	14	18	24	12	11	34	9	14
	SSP2	31	35	24	61	29	34	30	38	25	59	29	34	28	28	19	56	21	29
	SSP5	43	21	25	88	55	59	45	22	25	91	56	62	39	16	20	85	47	55

glaciers presence scenario 2, except for ESMI based SSP1-mid-century. The mean glacier melt is expected to increase for mid-century between 39–88% and 7–23% and for end-century between 11–204% and 20–128% for ECE3 and ESMI based simulations, respectively. For the third glacier presence scenario, glacier melt is significantly reduced relative to all presence scenarios except for SSP5-end-century. The mean glacier melt is expected to decrease for mid-century between 19–49% and 18–71%, and for end-century, between 11–71% and 1–55% for ECE3 and ESMI based simulations, respectively.

The future precipitation inputs (rainfall and snow) are the same for all three glacier presence scenarios. The precipitation increases relative to the historical period for all future scenarios, but rainfall and snowmelt contribution changes are different in both GCMs. The ECE3 based precipitation increases rainfall from 39 to 154% for future periods. The snowmelt contribution increases in a few scenarios between 1 and 35% and decreases in others between 1 and 28%. For the end-century period, rainfall increases for a few scenarios and decreases for others, but the mean value still indicates rainfall increases from 5 to 21%. The snowmelt contributions are increasing between 1 and 71% and decreasing in a few scenarios between 1 and 50%. The increase in snowmelt contribution in a few scenarios could be associated with a change in the precipitation seasonality with more precipitation in winter. Temperature rise can cause the same precipitation as now in some basin elevations. The decline in snowmelt in a few scenarios contribution to the future scenario could be for two reasons. One is less precipitation to fall as snow due to higher temperature (remember the threshold temperature that decides precipitation as snow or rain). This will reduce overall snow cover and stored snow to contribute to the following melt season. Second is the basin's increased temperature relative to the historical period temperature, so snow may melt immediately after the snow event.

Although the current modelling employs an energy balance-based approach to simulate the glacier melt, proxy equations are temperature-based. Hence, more temperature refers to more energy available and more melt (Nazeer et al. 2023). For historical period simulations, the lowest elevation (a1) with the maximum temperature generates the second least melt, and the second-highest elevation (a9) generates the maximum melt. The temperature is extremely low at the highest altitude (a10) due to the extremely high elevation (5550–7889 m) with a mean of 6719 m), even though the glacier cover is the most substantial (27% of total glacier cover). Thus the melt from the glaciers at these altitudes is negligible.

For future simulations, the significant melt is generated from higher elevations due to high enough temperature to melt from all elevations. With about 30% of permanent glacier cover, the Hunza basin receives approximately 50% of its flow from glaciers. However, as this cover shrinks, runoff and the amount of water from glacial melt will also decrease. Hasson (2016) suggested that the glacier melt regime be enhanced under warmer climates for the far future scenario and, subsequently, the overall water availability rise. He further suggested this trend may continue until glaciers deplete or are reduced to a tipping point with significantly less melt contribution, and reduce the overall water availability.

2.5 Conclusion

The following few straightforward outcomes from the current study;

- The temperature rise is evident for all investigated scenarios, with a maximum increase of 10 °C.
- A surge in precipitation is also evident in future scenarios. Also, changes in their cycles, with reduced snow and increased rainfall, are expected.
- The glacier presence could significantly affect the hydrological regime with almost 50% flow contribution from glacier melt for current runoff. These contributions could increase up to 265% for the intact glacier scenario for ECE3 based SSP5-end-century scenario relative to the historical period glacier melt. For the glacier recession to 5000 m scenario, the melt contribution could decrease to 71% for ECE3 based SSP1-end-century.
- The base flow period could only be reduced to a few months with increased flow. The peak flow period could be extended.
- The future river runoff projections are uncertain, but increasing trends are evident overall. For the glacier recession to 5000 masl scenarios, runoff could decrease to 40% for ESMI based SSP1-end-century.
- Significant changes in land cover are expected under the projected warming and reduced glacier cover—which can severely affect the vulnerable populations living in downstream plains.

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