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High Mountain Areas
Supplementary Material

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Table of contents

SM2.1 Details of High Mountain Regional Glacier and Permafrost Areas

The regional glacier and permafrost areas shown in Figure 2.1 are listed in Table SM2.1. Glacier area is taken from the Randolph Glacier Inventory (RGI6.0, RGI Consortium (2017)) and includes all glaciers within the depicted regions boundaries. Permafrost area is taken from Obu et al. (2019) but restricted to only include the permafrost in mountains, as defined based on a ruggedness index larger than 3.5 (Gruber, 2012, Figure 2.1). Within each high mountain region, regional permafrost area is calculated on a grid with 30 arc-second resolution (~1 km), as the sum of fractional permafrost area multiplied by the area of each grid cell; permanent snow and ice are excluded and masked based on landcover data from the European Space Agency Climate Change Initiative (ESA CCI Land Cover).

Two global-scale permafrost modelling studies (Gruber, 2012; Obu et al., 2019) provide suitable data with models differing in input, model structure, and assumptions. The data by Obu et al. (2019), extended to the southern hemisphere, are used since they provide permafrost fractional area (permafrost probability) directly. Their model was forced by remotely sensed land surface temperature, land cover and ERA-Interim climate reanalysis data, and statistically accounted for sub-grid variability of ground temperature due to snow and land cover. By contrast, (Gruber, 2012) used heuristics and mean annual air temperature to derive an approximate index of fractional permafrost area. Bounds of uncertainty were estimated by using two forcing climate data sets (reanalysis data from National Centers for Environmental Prediction (NCEP) and data from the Climatic Research Unit, CRU TS 2.0), and several sets of model parameters, resulting in five maps in total. Assuming the index to represent the fractional permafrost area, aggregated results for high mountain permafrost areas are similar to the estimate based on Obu et al. (2019). For high mountain areas, the five models by Gruber (2012) yield areas varying from 3.6 to 5.2 million km^2 and the model of Obu et al. (2019) results in 3.7 million km^2. The percentage of permafrost in high mountain areas relative to the global permafrost area, computed separately for each model, is 27–29% for Gruber (2012) and 27% for Obu et al. (2019).

2SM

Table SM2.1 | Glacier and permafrost area in high mountain regions shown in Figure 2.1. Glacier area is from the Randolph Glacier Inventory (RGI6.0, RGI Consortium (2017)). Permafrost areas are based on Obu et al. (2019).

High Mountain Region	Glacier Area (km^2)	Permafrost Area (km^2)
Alaska	86,725	307,767
Western Canada and USA	14,524	256,254
Iceland	11,060	4,023
Scandinavia	2,949	8,306
Central Europe	2,092	7,124
Caucasus and Middle East	1,307	10,181
North Asia	2,410	2,234,058
High Mountain Asia	97,605	866,667
Low Latitudes	2,341	673
Southern Andes	29,429	27,172
New Zealand	1,162	180
All high mountain regions	251,614	3,722,405

SM2.2 Details of Studies on Temperature Observations and Projections

Table SM2.2 | Overview of studies reporting trends in past surface air temperature including mean annual, seasonal and monthly mean values of daily mean, minimum and maximum temperature, per high mountain region (as defined in Figure 2.1) with published observations. Global syntheses are listed at the top of the table. Obs. stations refers to observation stations. Elevations are in meters (m) above sea level.

Location	Temperature (temp.) indicator	Trend (°C per decade)	Time period	Dataset	Reference
Global syntheses					
>500 m, 30°N–70°N	Annual mean value of minimum daily temp.	0.21	1951–1989	250 obs. stations	Diaz and Bradley (1997)
<500 m, 30°N–70°N	Annual mean value of minimum daily temp.	0.04	"	993 obs. stations	"
>500 m with mean annual temp. from -5°C to 5°C	Mean annual temp.	0.23	1948–2002	269 obs. stations	Pepin and Lundquist (2008)
>500 m with mean annual temp. <-5°C or >5°C	Mean annual temp.	0.12	"	1,084 obs. stations	"
>500 m	Mean annual temp.	0.40	1982–2010	640 obs. stations	Zeng et al. (2015)

Location	Temperature (temp.) indicator	Trend (°C per decade)	Time period	Dataset	Reference
<500 m	Mean annual temp.	0.32	"	2,020 obs. stations	"
>500 m	Mean annual temp.	0.30	1961–2010	910 obs. stations	Wang et al. (2016)
<500 m	Mean annual temp.	0.24	"	1,742 obs. stations	"
>500 m	Winter mean temp.	0.4	1961–2010	739 obs. stations	Qixiang et al. (2018)
<500 m	Winter mean temp.	0.35	"	1,262 obs. station	"
Western Canada and USA					
Colorado and Pacific Northwest, <4,000 m	Annual mean value of minimum daily temp.	0.37	1979–2006	Gridded dataset (based on obs. stations without homogenization)	Diaz and Eischeid (2007)
>4,000 m	Annual mean value of minimum daily temp.	0.75	"	"	"
Mt. Washington, northeast USA, 1,905 m	Mean annual temp.	0.35	1970–2005	1 obs. station	Ohmura (2012)
Pinkham Notch, northeast USA, 613 m	Mean annual temp.	0.31	"	1 obs. station	"
Northwest USA	Annual mean value of minimum daily temp.	0.17	1981–2012	Gridded dataset (based on homogenized obs. station)	Oyler et al. (2015)
Whole North America, >500 m	Mean annual temp.	0.14	1948–1998	552 obs. stations	Pepin and Seidel (2005)
Central Europe					
Switzerland	Mean annual temp.	0.35	1959–2008	Gridded dataset (based on 91 homogenized obs. stations)	Ceppi et al. (2012)
"	Autumn mean temp.	0.17	"	"	"
"	Winter mean temp.	0.40	"	"	"
"	Spring mean temp.	0.39	"	"	"
"	Summer mean temp.	0.46	"	"	"
Switzerland	Mean annual temp.	0.13	1864–2016	Gridded dataset (based on 19 homogenized obs. stations)	Begert and Frei (2018)
Switzerland, 203–815 m	Mean annual temp.	0.35	1981–2017	47 obs. stations	Rottler et al. (2019)
Switzerland, 910–1,878 m	"	0.31	"	34 obs. stations	"
Switzerland, 1,968–3,850 m	"	0.25	"	12 obs. stations	"
Swiss Alps	Mean April temp.	0.51	1961–2011	6 obs. stations	Scherrer et al. (2012)
Jungfraujoch, 3,580 m	Mean annual temp.	0.43	1970–2011	1 obs. station	Ohmura (2012)
Sonnblick, 3,109 m	Mean annual temp.	0.30	1980–2011	1 obs. station	"
Col de Porte, 1,325 m	Winter mean temp. (December to April)	0.3	1960–2017	1 obs. station	Lejeune et al. (2019)
Mont-Blanc, 4,300 m	Mean temp. (from englacial obs.)	0.14	1900–2004	1 obs. site	Gilbert and Vincent (2013)
Trentino, 203–875 m	Mean annual temp.	0.49	1976–2010	12 obs. stations	Tudoroiu et al. (2016)
Trentino, 925–2,125 m	"	0.27	"	12 obs. stations	"
Abruzzo Region	Mean annual temp.	0.15	1951–2012	24 obs. stations	Scorzini and Leopardi (2019)
Central Pyrenees	Annual mean value of maximum daily temp.	0.11	1910–2013	155 obs. stations	Pérez-Zanón et al. (2017)
"	"	0.57	1970–2013	"	"
"	Annual mean value of minimum daily temp.	0.06	1910–2013	"	"
"	"	0.23	1970–2013	"	"
Caucasus and Middle East					
Whole area	Mean annual temp.	0.14	1958–2000	Reanalysis data	Diaz et al. (2003)
"	"	0.26	1974–1998	"	"
Central Palestinian Mountains	Mean annual temp.	0.33	1970–2011	6 obs. stations	Hammad and Salameh (2019)

Location	Temperature (temp.) indicator	Trend (ºC per decade)	Time period	Dataset	Reference
Southern Andes					
18ºS–42ºS	Mean annual temp.	–0.05	1950–2010	75 obs. stations	Vuille et al. (2015)
Central Andes, 10ºS–25ºS, free atmosphere (500 hPa)	Mean annual temp.	0.16–0.41	1979–2008	Reanalyses	Russell et al. (2017)
Subtropical Andes, 30ºS–37ºS	Winter mean temp.	0.4	1980–2005	Reanalysis	Zazulie et al. (2017)
"	"	0.2	"	Gridded observation dataset	"
"	Summer mean temp.	0.3	"	Reanalysis	"
"	"	No trend	"	Gridded observation dataset	"
Low Latitudes (Andes and Africa)					
Tropical Andes, 2ºN–18ºS	Mean annual temp.	0.13	1950–2010	546 obs. stations	Vuille et al. (2015)
La Paz, Bolivia	Mean annual temp.	-0.70	1985–2010	1 obs. station	Ohmura (2012)
East Africa	Mean annual temp.	0.18	1958–2000	Reanalysis	Diaz et al. (2003)
"	"	0.18	1974–1998	"	
South and East Africa, >500 m	Mean annual temp.	0.14	1948–1998	41 obs. stations	Pepin and Seidel (2005)
High Mountain Asia					
Hindu Kush Himalaya	Mean annual temp.	0.1	1901–2014	122 obs. stations	Krishnan et al. (2019)
"	"	0.2	1951–2014	"	"
Mukteshwar, India, 2,311 m	Mean annual temp.	0.48	1980–2010	1 obs. station	Ohmura (2012)
Toutouhe, China, 4,535 m	Mean annual temp.	0.02	1970–2005	1 obs. station	"
Himalaya	Mean annual temp.	0.06	1958–2000	Reanalysis	Diaz et al. (2003)
"	"	0.23	1974–1998	"	"
Tibetan Plateau	Mean temp., wet season (May to September)	0.40	1979–2011	83 obs. stations	Gao et al. (2015)
"	Mean temp., dry season (October to April)	0.54	"	"	"
Tibetan Plateau, >3000 m	Mean annual temp.	0.69	1981–2006	47 obs. stations	Qin et al. (2009)
Tibetan Plateau, 1,000–3,000 m	"	0.55	"	24 obs. stations	"
Tibetan Plateau, 4,500–5,000 m	Mean value of winter minimum daily temp.	0.85	1961–2006	Obs. stations.	Liu et al. (2009)
"	Annual mean value of minimum daily temp.	0.53	"	Obs. stations.	"
Tibetan Plateau, >2,000 m	Mean value of winter minimum daily temp.	0.61	"	116 obs. stations.	"
"	Annual mean value of minimum daily temp.	0.42	"	"	"
Tibetan Plateau, >2,000 m	Mean annual temp.	0.16	1955–1996	97 obs. stations	Liu and Chen (2000)
"	Winter mean temp.	0.32	"	97 obs. stations	"
China 600–800 m	Mean annual temp.	0.05	1961–1990	12 obs. stations	"
Tibetan Plateau, 2,400–2,600 m	Mean annual temp.	0.15	"	4 obs. stations	"
Tibetan Plateau, 4,200–4,400 m	Mean annual temp.	0.25	"	6 obs. stations	"
Tibetan Plateau, >2,000 m	Mean annual temp.	0.28	1961–2007	72 obs. stations	Guo et al. (2012)
Tibetan Plateau, >2,000 m	Winter mean temp.	0.40	1961–2004	71 obs. stations	You et al. (2010a)
"	Summer mean temp.	0.20	"	"	"
"	Mean annual temp.	0.25	"	"	"
Tibetan Plateau	Winter mean temp.	0.37	1961–2001	ERA40 Reanalysis	You et al. (2010b)
"	Summer mean temp.	0.17	"	"	"
	Mean annual temp.	0.23	"	"	"
Indian Himalaya	Mean annual temp.	0.16	1901–2002	3 obs. stations	Bhutiyani et al. (2007)
Himalaya (Nepal), 1,200–2,000 m	Annual mean value of maximum daily temp.	0.57	1963–2009	3 obs. station	Nepal (2016)
Himachal Pradesh	Winter mean temp.	0.23	1975–2006	4 obs. stations	Dimri and Dash (2012)
Kashmir	Winter mean temp.	0.2	1975–2006	12 obs. stations	"
Australia					
Australia, >500 m	Mean annual temp.	0.16	1948–1998	14 obs. stations	Pepin and Seidel (2005)
Japan					
Fuji San, 3,775 m	Mean annual temp.	0.35	1985–2005	1 obs. station	Ohmura (2012)

Table SM2.3 | Overview of studies reporting future trends in surface air temperature including mean annual, seasonal and monthly mean values of daily mean, minimum and maximum temperature, per high mountain region (as defined in Figure 2.1). Global syntheses are listed at the top of the table. Obs. stations refer to observation stations. GCM is General Circulation Model. RCM is Regional Climate Model. Elevations are in meters (m) above sea level. CMIP5 is Coupled Model Intercomparison Project Phase 5. SRES is Special Report on Emissions Scenarios. RCP is Representative Concentration Pathway.

Location	Temperature (temp.) indicator	Change (°C per decade)	Time period	Scenario	Method	Reference
Global scale						
13 mountain ranges	Mean annual temp.	0.48	1961–1990 vs 2070–2099	SRES-A1F1	Downscaled GCMs	Nogués-Bravo et al. (2007)
13 mountain ranges	Mean annual temp.	0.25	1961–1990 vs 2070–2099	SRES B1	"	"
Alaska						
North America, >55°N	Mean annual temp.	0.61	1961–1990 to 2070–2099	SRES A1F1	Downscaled GCMs	Nogués-Bravo et al. (2007)
"	"	0.35	"	SRES B1	"	"
Western Canada and USA						
Colorado Rockies	Spring temp. (April)	up to 1	1995–2005 to 2045–2055	SRES A2	Pseudo global warming runs: RCMs	Letcher and Minder (2015)
North America, <55°N	Mean annual temp.	0.49	1961–1990 to 2070–2099	SRES A1F1	Downscaled GCMs	Nogués-Bravo et al. (2007)
North America, <55°N	Mean annual temp.	0.27	"	SRES B1	"	"
Iceland						
Full domain	Mean annual temp.	0.21–0.40	2000–2100	RCP8.5	Downscaled GCMs using RCMs	Gosseling (2017)
Central Europe						
European Alps	Mean annual temp.	0.25	1961–1990 to 2021–2050	SRES A1B	Downscaled GCMs using RCMs	Gobiet et al. (2014)
"	"	0.36	1961–1990 to 2069–2098	"	"	"
Switzerland	Mean annual temp.	0.14	1981–2010 to 2070–2099	RCP2.6	Downscaled GCMs using RCMs (EURO-CORDEX)	CH2018 (2018)
"	"	0.26	"	RCP4.5	"	"
"	"	0.49	"	RCP8.5	"	"
Austria	Mean annual temp.	0.23	1971–2000 to 2071–2100	RCP4.5	Downscaled GCMs using RCMs (EURO-CORDEX)	Chimani et al. (2016)
"	"	0.4	"	RCP8.5	"	"
Scandinavia						
Whole area, <500 m	Winter mean temp.	0.45	1961–1990 to 2070–2099	SRES A1B	Downscaled GCMs using RCMs	Kotlarski et al. (2015)
Whole area, ~1,500 m	Summer mean temp.	0.27	"	"	"	"
Whole area	Mean annual temp.	0.54	1961–1990 to 2070–2099	SRES A1F1	Downscaled GCMs	Nogués-Bravo et al. (2007)
"	"	0.31	1961–1990 to 2070–2099	SRES B1	Downscaled GCMs	"
Caucasus and Middle East						
Iran mountain areas	Mean annual temp.	0.45	1961–1990 to 2071–2000	SRES A2	Downscaled GCM	Babaeian et al. (2015)
"	"	0.30	"	SRES B2	"	
North Asia						
Whole area	Mean annual temp.	0.76	1961–1990 to 2070–2099	SRES A1F1	Downscaled GCMs	Nogués-Bravo et al. (2007)
"	"	0.43	"	SRES B1	"	"
Southern Andes						
Whole area	Mean annual temp.	0.34	1961–1990 to 2070–2099	SRES A1F1	Downscaled GCMs	Nogués-Bravo et al. (2007)
"	"	0.18	"	SRES B1	"	"
"	Winter and summer temp.	0.2	2006–2100	RCP4.5	CMIP5 GCMs	Zazulie et al. (2018)
"	"	~0.5	"	RCP8.5	"	"

Location	Temperature (temp.) indicator	Change (°C per decade)	Time period	Scenario	Method	Reference
Low Latitudes (Andes)						
Tropical Andes	Mean annual temp.	0.3	1961–2000 to 2080–2100	RCP8.5	Downscaled GCMs	Vuille et al. (2018)
Bolivian Andes	Mean annual temp.	0.34–0.4	1950–2000 to 2040–2069	SRES A1B	Downscaled GCMs	Rangecroft et al. (2016)
"	"	0.38–0.44	1950–2000 to 2070–2099	"	"	"
Quelccaya ice cap, Peru, 5,680 m	Mean annual temp.	0.25	2006–2100	RCP4.5	Bias corrected CMIP5 GCMs	Yarleque et al. (2018)
"	"	0.57	"	RCP8.5	"	"
High Mountain Asia						
Himalaya/ Tibetan Plateau, ~1,600 m	Mean value of winter minimum daily temp.	0.32	1971–2000 to 2071–2100	RCP8.5	CMIP5 GCMs	Palazzi et al. (2017)
Himalaya/ Tibetan Plateau, ~4,100 m	"	0.75	"	"	"	"
Hindu Kush Himalaya	Winter mean temp.	0.6	1976–2005 to 2066–2095	RCP8.5	RCMs	Sanjay et al. (2017)
	Summer mean temp.	0.54	"	"	"	"
Himalaya	Winter mean temp.	0.57	1970–2005 to 2070–2099	RCP8.5	RCMs	Dimri et al. (2018)
	Summer mean temp.	0.45	"	"	"	"
Tibetan Plateau, ~4,500 m	Mean annual temp.	0.65	2006–2050	RCP8.5	Downscaled GCMs	Guo et al. (2016)
Tibetan Plateau, 2,000–2,200 m	"	0.51	"	"	"	"
Kashmir Himalaya	Annual mean value of minimum daily temp.	0.07	1980–2010 to 2041–2070	RCP2.6	Downscaled GCM	Shafiq et al. (2019)
"	"	0.13	"	RCP8.5	"	"
"	"	0.04	1980–2010 to 2071–2100	RCP2.6	"	"
"	"	0.15	"	RCP8.5	"	"
"	Annual mean value of maximum daily temp.	0.11	1980–2010 to 2041–2070	RCP2.6	"	"
"	"	0.19	"	RCP8.5	"	"
"	"	0.08	1980–2010 to 2071–2100	RCP2.6	"	"
"	"	0.22	"	RCP8.5	"	"
New Zealand						
New Zealand	Mean annual temp.	0.33	1961–1990 to 2070–2099	SRES A1F1	Downscaled GCMs	Nogués-Bravo et al. (2007)
"	"	0.17	1961–1990 to 2070–2099	SRES B1	Downscaled GCMs	"

SM2.3 Details of Studies on Precipitation Observations and Projections

Table SM2.4 | Overview of recent studies providing evidence for past changes in precipitation, per high mountain region (as defined in Figure 2.1). Obs. stations refer to observation stations. Elevations are in meters (m) above sea level.

Location	Precipitation (precip.) indicator	Change	Time period	Dataset	Reference
Alaska					
Alaska	Annual precip.	Increase 8–40%, depending on the region	1949–2016	18 obs. stations	Wendler et al. (2017)
Western Canada and USA					
California	Winter precip.	Insignificant	1920–2014	Gridded dataset based on 102 obs. stations	Mao et al. (2015)
Canada	Ratio of snowfall to total precip.	Decrease, more pronounced in Western Canada	1948–2012	Gridded dataset based on obs. stations	Vincent et al. (2015)
Iceland					
Whole area	Winter precip.	Insignificant	1961–2000	Reanalysis and 40 obs. stations	Crochet (2007)

Location	Precipitation (precip.) indicator	Change	Time period	Dataset	Reference
Central Europe					
European Alps	Total precip.	Insignificant, dominated by internal variability	1901–2008	Gridded dataset based on obs. stations	Masson and Frei (2016)
European Alps	Daily precip.	Insignificant change due to high variability	1980–2010	43 obs. stations	Kormann et al. (2015a)
Swiss Alps	Fraction of days with snowfall over days with precip. (annual), <1,000 m	-20%	1961–2008	Subset within 52 obs. stations	Serquet et al. (2011)
"	", 1,000–2,000 m	-10 to -20%	"	"	"
"	", >2,000 m	-5%	"	"	"
"	Fraction of days with snowfall over days with precip. (spring), <1,000 m	-30 to -50%	"	Subset within 28 obs. stations	"
"	", 1,000–2,000 m	-10 to -30%	"	"	"
"	", >2,000 m	-5 to -10%	"	"	"
Abruzzo Region	Total precip.	-1.8% per decade (not significant)	1951–2012	46 obs. stations	Scorzini and Leopardi (2019)
Pyrenees	Total precip.	Insignificant decrease (-0.6% per decade)	1950–1999	24 obs. stations	López-Moreno (2005)
Carpathian mountain regions	Total precip.	No significant trend	1961–2010	Gridded data based on obs. stations	Spinoni et al. (2015)
Scandinavia					
Finland	Annual snowfall over total precip. ratio	Decrease (-1.9% per decade)	1909–2008	3 obs. stations	Irannezhad et al. (2017)
Caucasus and Middle East					
Greater Caucasus	Total precip.	-9 mm yr^{-1}	1936–2012	90 obs. stations	Elizbarashvili et al. (2017)
Adjara mountains	"	6 mm yr^{-1}	"	Subset of 90 obs. stations	"
Southern Andes					
Chile and Argentina	Annual precip.	General decrease (up to ~ -6 mm yr^{-1}) with positive values in the southwest corner of the region	1979–2010	Gridded dataset from obs. stations, and reanalyses	Rusticucci et al. (2014)
Subtropical Andes, 30ºS–37ºS	Winter precip.	<-0.1 mm d^{-1} per decade, insignificant	1980–2005	Gridded dataset from obs. stations, and reanalyses	Zazulie et al. (2017)
"	"	-0.1 mm d^{-1} per decade	1980–2005	"	"
"	Summer precip.	-0.3 mm d^{-1} per decade, insignificant	1980–2005	"	"
"	"	-0.2 mm d^{-1} per decade, insignificant	1980–2005	"	"
Low Latitudes (Andes and Africa)					
Claro River (Colombian Andean Central mountain range)	Annual precip.	Insignificant	1981–2003	7 obs. stations	Ruiz et al. (2008)
47 mountain protected areas in five national parks in the tropical belt (30ºS–30ºN, including Central America, South America, Africa, South Asia, Southeast Asia)	Annual precip.	Insignificant, except decrease in Africa	1982–2006	Gridded dataset from obs. stations, and reanalyses	Krishnaswamy et al. (2014)
Kenya	Precip.	Decrease (March to May, long rains) and increase (October to December, short rains).	1979–2011	50 obs. stations	Schmocker et al. (2016)
North Asia					
Northern Altai	Annual precip.	-0.14 mm yr^{-1}	1966–2015	9 obs. stations	Zhang et al. (2018)
Southern Altai	"	0.89 mm yr^{-1}	"	8 obs. stations	"

Location	Precipitation (precip.) indicator	Change	Time period	Dataset	Reference
High Mountain Asia					
Hindu-Kush Karakoram	Precip. (December to April)	Insignificant	1950–2010	Gridded dataset from obs. station, and reanalyses	Palazzi et al. (2013)
Himalaya	Precip. (June to September)	-0.021 to -0.01 mm d^{-1} yr^{-1}	1950–2009	〃	〃
Karakoram	Winter precip.	Significant increasing trend	1961–1999	17 obs. stations	Archer and Fowler (2004)
Middle and East Tian Shan	Snowfall fraction	Decrease, from 27 to 25%	1960–2014	Gridded dataset based on obs. stations	Chen et al. (2016)
West Tian Shan	Winter precip.	23%	1960–2014	*in situ*	〃
Monsoon-dominated regions, easternmost Himalaya	Annual precip. trend	-13.7 ± 2.4 mm yr^{-1}	1994–2012	7 obs. stations	Salerno et al. (2015)
〃	Precip. during monsoon months	-9.3 mm yr^{-1}	〃	〃	〃
Northwestern Indian Himalaya	Snowfall fraction	Significant decrease (3 out of 7 stations)	1991–2005	10 obs. stations	Bhutiyani et al. (2010)
〃	Winter precip. trend	Increasing but statistically insignificant	1866–2006	Subset of 10 obs. stations	〃
〃	Monsoon and annual precip. trend	Significant decreasing	〃	〃	〃
Tibetan Plateau	Annual precip.	1.43 mm yr^{-1}, large spatial variations	1960–2014	71 obs. stations	Deng et al. (2017)
Hengduan Mountain region	Annual precip.	Insignificant decrease	1961–2011	90 obs. stations	Xu et al. (2018)
	Spring precip.	Insignificant increase	〃	〃	〃
Hindu Kush Himalaya	95th percentile of precip.	Insignificant changes	1960–2000	Gridded datasets using obs. stations, 5 specific obs. stations	Panday et al. (2015)
New Zealand and Australia					
New Zealand	Annual precip.	Absence of marked trends, seasonally and geographically variable	1900–2010	294 obs. stations	Caloiero (2014); Caloiero (2015)
Southeast Australia	Annual precip.	Reduction since 1970s	1901–2012	Obs. stations	Grose et al. (2015)
Japan					
Whole region	Intense precip.	30% per century	1898–2003	Obs. stations (61 at daily time resolution)	Fujibe et al. (2005)
〃	Weak precip.	-20% per century	〃	〃	〃

Table SM2.5 | Overview of recent studies providing evidence for future changes in precipitation, per high mountain region (as defined in Figure 2.1). Obs. stations refer to observation stations. GCM is General Circulation Model. RCM is Regional Climate Model. SRES is Special Report on Emissions Scenarios. RCP is Representative Concentration Pathways. CMIP3 is Coupled Model Intercomparison Project Phase 3. CMIP5 is Coupled Model Intercomparison Project Phase 5. Elevations are in meters (m) above sea level.

Location	Precipitation (precip.) indicator	Change	Time period	Scenario	Method	Reference
Alaska						
South and Southeast Alaska	Snow day fraction	-15 to 7%	1970–1999 to 2040–2069	RCP4.5	Statistically downscaled GCMs	Littell et al. (2018)
〃	〃	-25 to 4%	〃	RCP8.5	〃	〃
〃	〃	-22 to 4%	1970–1999 to 2070–2099	RCP4.5	〃	〃
〃	〃	-41 to -6%	〃	RCP8.5	〃	〃
Western Canada and USA						
Western USA, 'Warm mountain sites'	Snowfall amount	-70 to -35%	1950–2005 to 2040–2069	RCP8.5	Statistically downscaled GCMs	Lute et al. (2015)
Western USA, 'Cold mountain sites'	〃	-20 to -5%	〃	〃	〃	〃

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Location	Precipitation (precip.) indicator	Change	Time period	Scenario	Method	Reference
Western USA, 'Warm mountain sites'	90% percentile of snowfall events	-30%	"	"	"	"
Western USA, 'Cold mountain sites'	90% percentile of snowfall events	5%	"	"	"	"
Southern California	Winter snowfall; 1,500–2,000 m	-40%	1981–2000 to 2041–2060	RCP2.6	Downscaled GCMs	Sun et al. (2016)
"	"; 2,000–2,500 m	-22%	"	"	"	"
"	"; >2,500 m	-8%	"	"	"	"
"	Winter snowfall; 1,500–2,000 m	-52%	"	RCP8.5	"	"
"	"; 2,000–2,500 m	-28%	"	"	"	"
"	"; >2,500 m	-11%	"	"	"	"
"	Winter snowfall; 1,500–2,000 m	-43%	1981–2000 to 2081–2100	RCP2.6	"	"
"	"; 2,000–2,500 m	-26%	"	"	"	"
"	"; >2,500 m	-13%	"	"	"	"
"	Winter snowfall; 1,500–2,000 m	-78%	"	RCP8.5	"	"
"	"; 2000–2500 m	-48%	"	"	"	"
"	"; >2500 m	-18%	"	"	"	"
Western Canada	Winter precip.	11%	1979–1994 to 2045–2060	RCP8.5	Downscaled GCMs	Erler et al. (2017)
"	"	17%	1979–1994 to 2085–2100	"	"	"
Iceland						
Whole area	Annual precip.	Insignificant	1981–2000 to 2081–2100	RCP4.5, RCP8.5	Downscaled GCMs using RCMs	Gosseling (2017)
Central Europe						
Greater Alpine Region	Winter precip.	12.3%	1971–2000 to 2071–2100	RCP4.5	5 EUROCORDEX GCM/RCM pairs	Smiatek et al. (2016)
"	Spring precip.	5.7%	"	"	"	"
"	Summer precip.	-1.7%	"	"	"	"
"	Autumn precip.	2.3%	"	"	"	"
"	Number of days with precip. >15 mm	10.9%	"	"	"	"
Alpine Region	Winter (December to February) precip.	8%	1981–2010 to 2020–2049	RCP4.5	EUROCORDEX GCM/RCM pairs (0.11°)	Rajczak and Schär (2017)
"	"	6%	"	RCP8.5	"	"
"	"	12%	1981–2010 to 2070–2100	RCP4.5	"	"
"	"	17%	"	RCP8.5	"	"
Switzerland	Annual precip.	0.6 %	1981–2010 to 2070–2099	RCP2.6	EUROCORDEX GCM/RCM pairs	CH2018 (2018)
"	Winter (December to February) precip.	8.8%	"	"	"	"
"	Annual precip.	3%	"	RCP4.5	"	"
"	Winter (December to February) precip.	12.9%	"	"	"	"
"	Annual precip.	3.3%	"	RCP8.5	"	"
"	Winter (December to February) precip.	23.7%	"	"	"	"
Austria	Annual precip.	7.1%	1971–2000 to 2071–2100	RCP4.5	EUROCORDEX GCM/RCM pairs	Chimani et al. (2016)
"	Winter (December to February) precip.	10.6%	"	"	"	"
"	Annual precip.	8.7%	"	RCP8.5	"	"
"	Winter (December to February) precip.	22.7%	"	"	"	"
Alps	Annual solid precip.	-25%	1981–2010 to 2070–2099	RCP4.5	EUROCORDEX GCM/RCM pairs (0.11°)	Frei et al. (2018)

Location	Precipitation (precip.) indicator	Change	Time period	Scenario	Method	Reference
"	"	-45%	"	RCP8.5	"	"
Pyrenees, <1,500 m	Frequency and intensity of heavy snowfall events	Decrease	1960–1990 to 2070–2100	SRES A2	Dynamically downscaled GCM	López-Moreno et al. (2011)
Pyrenees, >2,000 m	"	Insignificant except at high altitude (30% increase)	"	"	"	"
Pyrenees, >2,000 m	"	20–30%	"	SRES B2	"	"
Carpathian mountains	Summer precip.	Decrease by up to -20 mm per month	1971–2000 to 2071–2100	RCP8.5	Multiple GCM/RCM pairs	Alberton et al. (2017)
Scandinavia						
Scandinavian mountains (high elevation)	Annual snowfall	20%	1961–1990 to 2071–2100	SRES A1B	Multiple GCM/RCM pairs	Räisänen and Eklund (2012)
Caucasus and Middle East						
Iran mountain areas	Annual precip.	Precip. increase	1961–1990 to 2071–2000	SRES A2	Downscaled GCM	Babaeian et al. (2015)
"	"	"	"	SRES B2	"	
Alborz mountains	Annual precip., winter precip.	No significant change detected	1981–2000 to 2081–2100	RCP4.5, RCP8.5	3 CMIP5 GCMs	Zarenistanak (2018)
Low Latitudes (Andes)						
Subtropical Andes, 30°S–37°S	Winter and summer precip.	No clear trend	2006–2100	RCP4.5, RCP8.5	GCMs	Zazulie et al. (2018)
Tropical Andes	Annual precip.	Geographically variable. Precip. increase up to ~2,000 m. No significant changes on eastern slope >2,000 m, decrease in the western slope >4,000 m	1961–1990 to 2071–2100	SRES A2, B2	Downscaled GCM	Urrutia and Vuille (2009)
Central Andes	Annual precip.	-19 to -33%	1961–2010 to 2071–2100	RCP8.5	Multiple GCMs	Neukom et al. (2015)
High Mountain Asia						
Himalaya	Summer precip.	0.008–0.014 mm d^{-1} yr^{-1}	2006–2100	RCP8.5	GCM multi-member ensemble	Palazzi et al. (2013)
Eastern Himalaya	Annual precip.	15–27% (most in summer)	1970–1999 to 2070–2099	SRES B1, A1B, A2 and RCP8.5	CMIP3 and CMIP5 GCMs	Panday et al. (2015)
Western Himalaya-Karakoram	Annual precip.	1–5% (due to increase in winter precip.)	"	"	"	"
Hindu Kush Himalaya	Daily 99% precip. quantile	50% on average	1981–2010 to 2071–2100	RCP8.5	Downscaled GCMs	Wijngaard et al. (2017)
Northwest Himalaya and Karakoram	Precip., June to September	-0.1%	1976–2005 to 2036–2065	RCP4.5	CORDEX GCM/RCM pairs	Sanjay et al. (2017)
"	Precip., December to April	7%	"	"	"	"
"	Precip., June to September	3.5%	1976–2005 to 2066–2095	"	"	"
"	Precip., December to April	14.1%	"	"	"	"
"	Precip., June to September	3.7%	1976–2005 to 2036–2065	RCP8.5	"	"
"	Precip., December to April	12.8%	"	"	"	"
"	Precip., June to September	3.9%	1976–2005 to 2066–2095	"	"	"
"	Precip., December to April	12.9%	"	"	"	"
Central Himalaya	Precip., June to September	4.4%	1976–2005 to 2036–2065	RCP4.5	"	"
"	Precip., December to April	-0.7%	"	"	"	"
"	Precip., June to September	10.5%	1976–2005 to 2066–2095	"	"	"

Location	Precipitation (precip.) indicator	Change	Time period	Scenario	Method	Reference
"	Precip., December to April	1.5%	"	"	"	"
"	Precip., June to September	9.1%	1976–2005 to 2036–2065	RCP8.5	"	"
"	Precip., December to April	-1.3%	"	"	"	"
"	Precip., June to September	19.1%	1976–2005 to 2066–2095	"	"	"
"	Precip., December to April	-8.8%	"	"	"	"
Southeast Himalaya and Tibetan Plateau	Precip., June to September	6.8%	1976–2005 to 2036–2065	RCP4.5	"	"
"	Precip., December to April	3.1%	"	"	"	"
"	Precip., June to September	10.4%	1976–2005 to 2066–2095	"	"	"
"	Precip., December to April	3.7%	"	"	"	"
"	Precip., June to September	10.2%	1976–2005 to 2036–2065	RCP8.5	"	"
"	Precip., December to April	0.9%	"	"	"	"
"	Precip., June to September	22.6%	1976–2005 to 2066–2095	"	"	"
"	Precip., December to April	0.6%	"	"	"	"
Tibetan Plateau	Annual precip.	3.2%	1961–2005 to 2006–2035	RCP2.6, RCP8.5	CMIP5 GCMs	Su et al. (2013)
"	"	6%	1961–2005 to 2036–2099	RCP2.6	"	"
"	"	12%	"	RCP8.5	"	"
Eastern Tibetan Plateau	Annual snowfall	-15%	1986–2005 to 2080–2099	RCP4.5	RCM driven by several GCMs	Zhou et al. (2018)
Kashmir Himalaya	Annual precip.	9%	1980–2010 to 2041–2070	RCP2.6	Downscaled GCM	Shafiq et al. (2019)
"	"	12%	"	RCP8.5	"	"
"	"	11%	1980–2010 to 2071–2100	RCP2.6	"	"
"	"	14%	"	RCP8.5	"	"
Northern Tian Shan	Annual precip.	5%	1976–2005 to 2070–2099	RCP8.5	CMIP5 GCMs	Yang et al. (2017)
Western Tian Shan and northern Kunlun Mountains	Solid precip.	-26.5%	"	"	"	"
Australia						
Southeast Australia	Annual precip.	-5% (high variability)	1950–2005 to 2020–2039	RCP2.6	Downscaled GCMs	Grose et al. (2015)
"	"	-5% (high variability)	"	RCP8.5	"	"
"	"	-5% (high variability)	1950–2005 to 2080–2099	RCP2.6	"	"
"	"	-10% (high variability)	"	RCP8.5	"	"
Japan						
Tokai region	99th percentile of daily precip.	10–50% in winter (December to February)	1984–2004 to 2080–2100	RCP8.5	Single dynamically downscaled GCM (MRI AGCM)	Murata et al. (2016)
Central Japan	Winter snowfall (November to March)	Decrease in most parts of Japan (up to 300 mm), increase in the central part of northern Japan	1950–2011 to 2080–2099	4°C warming in 2080–2099 with respect to 1861–1880, under RCP8.5	MRI-AGCM3.2 (dynamically downscaled)	Kawase et al. (2016)
"	Heavy snowfall (10 years return period)	Increase (10 mm) in the inland areas of central and northern Japan	"	"	"	"

SM2.4 Details of Studies on Snow Cover Observations and Projections

Table SM2.6 | Synthesis of recent studies reporting past changes in snow cover in high mountain areas, per high mountain region (as defined in Figure 2.1). SWE is snow water equivalent. Obs. stations refer to observation stations. Elevations are in meters (m) above sea level.

Location	Snow variable	Change	Time period	Dataset	Reference
Alaska					
Whole area	Duration	Decrease	20th century	Remote sensing	Brown et al. (2017)
"	SWE	Decrease	20th century	"	"
Mountainous Alaska	Snow at high elevation	Increase	1840–present	Indirect evidence from glacier accumulation	Winski et al. (2017)
Western Canada and USA					
Western USA	Springtime SWE	Decrease for 92% stations	1955–present	*In situ* observations	Mote et al. (2018)
"	April 1 SWE	-15 to -30%	1955–present	"	"
Western USA	Annual maximum SWE	Decrease by 41% on average for 13% of pixels	1982–2016	Gridded product based on *in situ* observations	Zeng et al. (2018)
Canada	Duration	Decrease 2–12 days per decade	1950–2012	*In situ* observations	DeBeer et al. (2016)
Iceland					
Whole area	Duration	Decrease 0–10 days per decade	1980–2010	Remote sensing	Brown et al. (2017)
Central Europe					
European Alps and Pyrenees	Snow depth	Decrease at low elevation, step decrease in late 1980s	Mid 20th century–present	*In situ*, reanalyses	Beniston et al. (2018) Reid et al. (2016)
European Alps	SWE	Decrease at low elevation, step decrease in late 1980s	Mid 20th century–present	54 obs. stations	Marty et al. (2017b)
European Alps	Duration	Insignificant trend, decrease at 700–900 m in the southeast and southwest Alps	1985–2011	Optical remote sensing	Hüsler et al. (2014)
Swiss Alps	Onset date	12 days later on average	1970–2015	11 obs. stations	Klein et al. (2016)
"	Melt-out date	26 days earlier on average	"	"	"
Austrian Alps, 500–2,000 m	Snow cover days	-13 to -18 depending on the region	1950–1979 to 1980–2009	Modelling based on *in situ* observations	Marke et al. (2018)
Austrian Alps, 2,000– 2,500 m	"	-12 to -14 depending on the region	"	"	"
Austrian Alps, >2,500 m	"	-20 (central Austria)	"	"	"
French Alps, 1,800 m	Duration	-24 days	1958–2009	Local reanalysis	Durand et al. (2009)
French Alps	Melt onset	2 weeks earlier >3,000 m	1980–2015	*In situ* observations	Thibert et al. (2013)
"	Melt intensity	15% stronger >3,000 m	"	*In situ* observations and modelling	"
Pyrenees, <1,000 m	Snow cover duration	Decrease in majority of stations	1975–2002	*In situ* observations	Pons et al. (2010); Beniston et al. (2018)
Pyrenees, >1,000 m	"	Decrease in majority of stations		"	"
Pyrenees, Andorra, 1,645 m	Number of days with snow depth above 5, 30 and 50 cm	Increase until ~1980 then decrease (not statistically significant, high variability)	1935–2015	*In situ* observations	Albalat et al. (2018)
Scandinavia					
Norway	Snow depth and SWE	Decrease at low elevation	20th century	*In situ* observations	Skaugen et al. (2012); Dyrrdal et al. (2013); Beniston et al. (2018)
"	"	Increase at higher elevation	20th century	"	"
Northern Finland	Snow cover duration	-2.4 days per decade	1961–2014	Gridded dataset based on *in situ* observations	Luomaranta et al. (2019)
Southern Finland	"	-5.7 days per decade	"	"	"
Caucasus and Middle East					
Central Caucasus, 2,300 m	Amount of winter snow	Declining since late 1980s	1968–2013	*In situ* observations	Volodicheva et al. (2014)
Northwestern Iran	Snow cover duration and mean snow depth	Decrease at most stations	1981–2011	28 *in situ* observations	Arkian et al. (2014)

Location	Snow variable	Change	Time period	Dataset	Reference
Southern Andes					
Whole area	Snow covered area	Insignificant decrease (high variability)	2000–2015	Optical remote sensing	Malmros et al. (2018)
Whole area	Snow covered area	Decrease	1979–2006	Passive microwave satellite	Le Quesne et al. (2009)
Low Latitudes (including tropical Andes)					
Compared to mid and high latitude mountain areas seasonal snow cover has limited relevance in the tropical Andes and other tropical areas, except in the immediate vicinity of glaciers. Satellite-based observations are too short to address long-term trends.					Saavedra et al. (2018)
High Mountain Asia					
Himalaya and Tibetan Plateau	Snow covered area	Insignificant trend (high variability compared to record length)	2000–2015	Optical remote sensing	Tahir et al. (2015); Gurung et al. (2017); Bolch et al. (2019); Li et al. (2018)
Himalaya	SWE	-10.60 kg m^{-2} yr^{-1} for areas >500 m	1987–2009	Passive microwave remote sensing	Smith and Bookhagen (2018); Wang et al. (2018)
Australia					
Southeast Australia	SWE	Reduction, especially in springtime	Mid-20th century–present	*In situ* observations	Fiddes et al. (2015); Di Luca et al. (2018)
"	Duration	Reduction, especially in springtime	"	"	"

Table SM2.7 | Synthesis of recent studies reporting 21st century projections in snow cover in high mountain areas, per high mountain region (as defined in Figure 2.1). SWE is snow water equivalent. GCM is General Circulation Model. RCM is Regional Climate Model. RCP is Representative Concentration Pathways. CMIP5 is Coupled Model Intercomparison Project Phase 5.

Location	Snow variable	Change	Time period	Scenario	Method	Reference
Alaska						
Mountainous Alaska	SWE	-10 to -30%	1970–1999 to 2040–2069	RCP8.5	Multiple GCM/RCM pairs	Littell et al. (2018)
"	SWE	-40 to -60%	1970–1999 to 2070–2099	"	"	"
Western Canada and USA						
Western USA	April 1 SWE	-50%	1965–2005 to 2010–2040	RCP8.5	Multiple GCM/RCM pairs	Naz et al. (2016)
"	Duration	-10 to -100 days	1976–2005 to 2071–2100	RCP8.5	"	Musselman et al. (2018)
"	Peak annual SWE	-6.2 kg m^{-2} per decade	2013–2038	RCP8.5	Post-processed CMIP5 GCM	Fyfe et al. (2017)
Iceland						
Low elevation	Snow depth	-100%	1981–2000 to 2081–2100	RCP8.5	Single RCM	Gosseling (2017)
Top of central Vatnajökull	Snow depth	20%	1981–2000 to 2081–2100	"	"	"
Central Europe						
European Alps	Winter SWE <1,500 m	-40%	1971–2000 to 2020–2049	SRES A1B	Multiple GCM/RCM pairs	Steger et al. (2012); Gobiet et al. (2014); Beniston et al. (2018)
"	"	-70%	1971–2000 to 2070–2099	"	"	"
"	Winter SWE > 2,500 m	-10%	1971–2000 to 2020–2049	"	"	"
"	"	-40%	1971–2000 to 2070–2099	"	"	"
French Alps, 1,500 m	Winter snow depth	-20%	1986–2005 to 2030–2050	RCP2.6	Adjusted multiple GCM/RCM pairs	Verfaillie et al. (2018)
"	"	-30%	"	RCP8.5	"	"
"	"	-30%	1986–2005 to 2080–2100	RCP2.6	"	"
"	"	-80%	"	RCP8.5	"	"
European Alps	Similar results as above and strengthening of the asymmetrical seasonal snow decline pattern (stronger trend for reduced snow cover duration in spring than in autumn).					Marty et al. (2017a); Terzago et al. (2017) Hanzer et al. (2018)

Location	Snow variable	Change	Time period	Scenario	Method	Reference
Scandinavia						
Northern Scandinavia	Duration and SWE	Decrease at low elevation, marginal changes at high elevation	1971–2000 to 2010–2100	A1B	GCM downscaled using RCM	Räisänen and Eklund (2012); Beniston et al. (2018)
Norway	Duration	-14 to -32%	1981–2010 to 2021–2050	RCP4.5	Adjusted multiple GCM/RCM pairs	Scott et al. (2019)
"	"	-15 to -50%	"	RCP8.5	"	"
"	"	-34 to -64%	1981–2010 to 2071–2100	RCP4.5	"	"
"	"	-38 to -89%	"	RCP8.5	"	"
Caucasus and Middle East						
West Caucasus, 567 m	Snow cover duration	-35 to 40%	1991–2000 to 2041–2050	B2	Downscaled GCM	Sokratov et al. (2014)
Southern Andes						
Whole area	Mean SWE	-13%	1980–2010 to 2035–2065	RCP4.5	Multiple RCM	López-Moreno et al. (2017)
"	"	-17%	"	RCP8.5	"	"
"	Duration	-7 days	"	RCP4.5	"	"
"	"	-10 days	"	RCP8.5	"	"
Limarí river basin, north central Chile	Peak SWE (>5,000 m)	-32%	1961–1990 to 2071–2000	B2	Single GCM/RCM pair	Vicuña et al. (2011)
"	"; 2,500–3,000 m	-82%	"	"	"	"
"	"; 2,000–2,500 m	-100%	"	"	"	"
"	Peak SWE (>5,000 m)	-41%	"	A2	"	"
"	"; 2,500–3,000 m	-96%	"	"	"	"
"	"; 2,000–2,500 m	-100%	"	"	"	"
High Mountain Asia						
Hindu Kush and Karakoram	Winter snow depth (December to April)	-7%	1986–2005 to 2031–2050	RCP8.5	Multiple GCMs	Terzago et al. (2014)
"	"	-28%	1986–2005 to 2081–2100	"	"	"
Himalaya	"	-25%	1986–2005 to 2031–2050	"	"	"
"	"	-55%	1986–2005 to 2081–2100	"	"	"
New Zealand and Australia						
Australia	SWE	Reduction, especially below 1,000 m	1980–1999 to 2030–2049	SRES A1B	Multiple downscaled GCMs	Hendrikx et al. (2013)
Australia	SWE	-15%	1990–2009 to 2020–2040	SRES A2	Multiple downscaled GCMs	Di Luca et al. (2018)
"	"	-60%	1990–2009 to 2060–2080	"	"	"
New Zealand	SWE; 1,000 m	-3 to -44%	1980–1999 to 2030–2049	SRES A1B	Multiple downscaled GCMs	Hendrikx et al. (2012)
"	"; 2,000 m	-8 to -22%	"	"	"	"
"	"; 1,000 m	-32 to -79%	1980–1999 to 2080–2099	"	"	"
"	"; 2,000 m	-6 to -51%	"	"	"	"
Japan						
Japan	Winter snow depth, low elevation	-50%	Base: 1990s Future: time period corresponding to 2°C warming	2°C global warming (from SRES A1B)	Multiple downscaled GCMs (time sampling)	Katsuyama et al. (2017)
"	"; high elevation	-10%	"	"	"	"
mountain catchment	SWE	-36%	1981–2000 to 2046–2065	SRES A1B	Multiple downscaled GCMs	Bhatti et al. (2016)

SM2.5 Details on Climate Models used in Figure 2.3

Table SM2.8 | List of Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Models (GCM) and where available, Regional Climate Models (RCM) used for projecting the winter and summer air temperature (T) and snow water equivalent (SWE), for Representative Concentration Pathway (RCP)2.6 and RCP8.5, for the five regions represented in Figure 2.3: Rocky Mountains in North America, Subtropical Central Andes, European Alps, Hindu Kush and Karakoram, and Himalaya. For the Rocky Mountains, Hindu Kush and Karakoram, and Himalaya only RCP8.5 data were used.

		Rocky Mountains		Subtropical Central Andes				European Alps				Hindu Kush and Karakoram; Himalaya	
GCM (default is r1i1p1)	RCM (driven by corresponding GCM)	RCP8.5		RCP2.6		RCP8.5		RCP2.6		RCP8.5		RCP8.5	
		T	SWE	T	SWE	T	SWE	T	SWE	T	SWE	T	SWE
ACCESS1-0						X						X	
ACCESS1-3						X						X	
Bcc-csm1-1				X		X						X	
BNU-ESM												X	
CanESM2												X	
	CCCma-CanRCM4	X	X										
	UQAM-CRCM5	X	X										
CCSM4				X	X	X	X					X	
CESM1-BGC						X						X	X
CESM1-CAM5				X	X	X	X					X	
CMCC-CM						X							X
CNRM-CM5				X	X	X	X					X	
	CLMcom-CCLM4-8-17									X	X		
	CNRM-ALADIN53							X		X	X		
	SMHI-RCA4									X			
CSIRO-Mk3-6-0												X	
EC-Earth (r8i1p1)													X
EC-EARTH				X		X							
FGOALS-g2												X	
GFDL-CM3												X	
GFDL-ESM2G												X	
	NCAR-WRF	X	X										
GISS-E2-R												X	
HadGEM2-CC						X						X	
HadGEM2-ES				X		X							
	NCAR-WRF	X	X										
	CLMcom-CCLM4-8-17									X	X		
	SMHI-RCA4									X			
ICHEC-EC-EARTH (r12i1p1)													
	CLMcom-CCLM4-8-17									X	X		
	SMHI-RCA4							X		X			
ICHEC-EC-EARTH (r3i1p1)													
	DMI-HIRHAM5							X		X			
IPSL-CM5A-LR												X	
IPSL-CM5A-MR												X	
	SMHI-RCA									X			
IPSL-CM5B-LR												X	
MIROC5				X		X						X	
MIROC-ESM-CHEM												X	
MIROC-ESM												X	

		Rocky Mountains		Subtropical Central Andes				European Alps				Hindu Kush and Karakoram; Himalaya	
GCM (default is r1i1p1)	RCM (driven by corresponding GCM)	RCP8.5		RCP2.6		RCP8.5		RCP2.6		RCP8.5		RCP8.5	
		T	SWE	T	SWE	T	SWE	T	SWE	T	SWE	T	SWE
MRI-CGCM3				X	X	X	X					X	
MPI-M-MPI-ESM-LR													
	NCAR-WRF	X	X										
	UQAM-CRCM5	X	X										
	CLMcom-CCLM4-8-17									X	X		
	MPI-CSC-REMO2009							X	X	X	X		
	SMHI-RCA4									X			
MPI-M-MPI-ESM-LR (r2i1p1)													
	MPI-CSC-REMO2009							X	X	X	X		
MPI-M-MPI-ESM-MR													
	UQAM-CRCM5	X	X										
MRI-ESM1						X	X						
NorESM1-M												X	
Ensemble members		*7*	*7*	*8*	*4*	*14*	*5*	*5*	*2*	*13*	*7*	*23*	*3*

SM2.6 Synthesis of Recent Studies Reporting on Past and Projected Changes of River Runoff

Table SM2.9 | Synthesis of recent studies reporting on past and projected changes in river runoff, per high mountain region (as defined in Figure 2.1). Entries per region are sorted according to increasing percentage of glacier cover for past and projected changes separately. Note that studies on annual runoff that are listed in Table SM2.10 are not listed here. The year of peak water given there indicates the year before which annual runoff is increasing and beyond which it is decreasing. RCP is Representative Concentration Pathway. GCM is General Circulation Model. SRES is Special Report on Emissions Scenario.

Location	Basin area (% glacier cover)	Variable (change)	Cause	Time period	Method	Scenario	Reference
Global-scale							
97 snow sensitive basins in 421 basins in northern hemisphere	(glacier melt not considered in model)	Spring to summer snowmelt runoff (decrease)	Transition of snowfall to rainfall	1955–2005 to 2006–2080	Model, 19 GCMs	RCP8.5	Mankin et al. (2015)
Alaska							
Gulf of Alaska	420,300 km^2 (17%)	Annual runoff (1–2 km^3 yr^{-1})	Increased glacier melt	1980–2014	Model	Past	Beamer et al. (2016)
Gulkana, Wolverine	24.6 km^2 and 31.5 km^2 (>50%)	Summer runoff (increase)	Increased glacier melt	1966–2011	2 stream gauges	Past	O'Neel et al. (2014)
Gulf of Alaska	420,300 km^2	Annual runoff (25–46%)	Increased glacier melt	1984–2014 to 2070–2099	Downscaled GCMs	RCP4.5 RCP8.5	Beamer et al. (2016)
"	"	December to February runoff (93–201%)	Transition of snowfall to rainfall	"	"	"	"
"	"	Spring peak (1 month earlier)	Earlier snowmelt	"	"	"	"

Location	Basin area (% glacier cover)	Variable (change)	Cause	Time period	Method	Scenario	Reference
Western Canada and USA							
South and Central Columbia Basin	0.1–19%	August runoff (decrease)	Decreased snow and glacier melt	1975–2012	20 stream gauges, hydro-graph separation	Past	Brahney et al. (2017)
Canadian Rocky Mountains and adjacent ranges	166–1,170 km^2 (0–23.4%), no data in some basins	Summer runoff (decrease in glacierized basins)	Decreased glacier melt, decreased precipitation	1955–2010, depending on sites	6 stream gauges	Past	Fleming and Dahlke (2014)
Bridge river, British Columbia (Canada)	139 km^2 (52.6% in 2014)	Winter runoff (increase)	Increased glacier melt	1979–2014	Stream gauge	Past	Moyer et al. (2016)
〃	〃	Summer runoff (decrease)	Decreased glacier melt	〃	〃	〃	〃
Sierra Nevada, northeast of California (USA)	4,781 km^2 (0%)	Winter runoff (~19%)	Transition of snowfall to rainfall, increased precipitation	1964–2014 to 2015–2064	7 GCMs	RCP4.5, RCP8.5	Sultana and Choi (2018)
〃	〃	Spring peak (1 month early)	Earlier snowmelt	〃	〃	〃	〃
Athabasca (Canada)	161,000 km^2 (0%)	Summer runoff (6–76 %)	Increased snowmelt, increased precipitation	1983–2013 to 2061–2100	Downscaled 1 GCM	RCP4.5, RCP8.5	Shrestha et al. (2017)
〃	〃	Winter runoff (3–114%)	Transition of snowfall to rainfall	〃	〃	〃	〃
Whole USA	(not significant)	Winter runoff (increase in snow dominated basins)	Transition of snowfall to rainfall	1961–2005 to 2011–2050	Downscaled 10 GCMs	RCP8.5	Naz et al. (2016)
〃	〃	Spring peak (earlier in snow-dominated basins)	Earlier snowmelt	〃	〃	〃	〃
Western North America	(not significant)	Winter runoff (increase)	Transition of snowfall to rainfall	1965–2005 to 2010–2050	Downscaled 10 GCMs	RCP8.5	Pagán et al. (2016)
〃	〃	Summer runoff (decrease)	Decreased snowmelt	〃	〃	〃	〃
〃	〃	Spring peak (6–11 days earlier)	Earlier snowmelt	〃	〃	〃	〃
Western USA	(not significant)	Spring peak (1.5–4 weeks early)	Earlier snowmelt	1960–2005 to 2080–2100	Downscaled 10 GCMs	RCP4.5, RCP8.5	Li et al. (2017)
British Columbia	0–8%	Winter runoff (45–95%)	Increased snowmelt, increased rainfall	1961–1990 to 2041–2070	Downscaled 8 GCMs	SRES B1, A1B	Schnorbus et al. (2014)
〃	〃	Summer runoff (-58 to -9%)	Decreased snowmelt, transition of snowfall to rainfall	〃	〃	〃	〃
Nooksack (USA)	2,000 km^2 (<1%)	Winter runoff (39–88%)	Transition of snowfall to rainfall	1950–1999 to 2060–2090	Downscaled 3 GCMs	SRES A2, B1	Dickerson-Lange and Mitchell (2014)
〃	〃	Summer runoff (-50 to -26%)	Decreased snowmelt	〃	〃	〃	〃
〃	〃	Spring peak (1 month early)	Earlier snowmelt	〃	〃	〃	〃
〃	〃	Annual peak (increase, 1 month later)	Decreased snowmelt, increased extreme precipitation	〃	〃	〃	〃
Fraser, North America	240,000 km^2 (1.5%)	Winter runoff (increase)	Transition of snowfall to rainfall	1980–2009 to 2040–2069	Downscaled 12 GCMs	RCP4.5 RCP8.5	Islam et al. (2017)
〃	〃	Summer runoff (decrease)	Decreased snowmelt, transition of snowfall to rainfall	〃	〃	〃	〃
〃	〃	Annual peak (20–30 days earlier)	Earlier snowmelt	〃	〃	〃	〃

Location	Basin area (% glacier cover)	Variable (change)	Cause	Time period	Method	Scenario	Reference
Central Europe							
Alps	(some including glaciers)	Winter runoff (increase in glacier- or snow-dominated basins)	Transition of snowfall to rainfall	1961–2005	177 stream gauges	Past	Bard et al. (2015)
〃	〃	Spring peak (earlier)	Earlier snowmelt and glacier melt	〃	〃	〃	〃
Alps (northern Italy)	~100–10,000 km^2 (some including glaciers)	Winter runoff (increase at >1,800 m above sea level)	Transition of snowfall to rainfall	1921–2011	23 stream gauges	Past	Bocchiola (2014)
〃	〃	Summer runoff (decrease)	Decreased snowmelt and glacier melt, increased evapotranspiration	〃	〃	〃	〃
Western Austria	(0–71.9%)	Annual flow (increase at high elevations, decrease at low elevations)	Increased and decreased glacier melt	1980–2010	32 stream gauges	Past	Kormann et al. (2015b)
Middle and upper Rhine	144,231 km^2 (<1%)	Winter runoff (4–51%)	Transition of snowfall to rainfall, earlier snowmelt	1979–2008 to 2021–2050 and 2070– 2099	10 GCM-RCMs	SRES A1B	Bosshard et al. (2014)
〃	〃	Summer runoff (-40 to -9%)	Decreased snowmelt	〃	〃	〃	〃
Gigerwaldsee (Switzerland)	97 km^2 (<1%)	Summer runoff (decrease)	Decreased glacier melt	1992–2021 to 2035–2064 and 2069–2098	7 GCM-RCMs	SRES A1B	Etter et al. (2017)
Swiss Alps	20–1,577 km^2 (0–4%)	Summer runoff (-32 to -56%)	Transition of snowfall to rainfall, Earlier snowmelt	1980–2009 to 2070–2099	10 GCM-RCMs	SRES A1B	Jenicek et al. (2018)
Swiss Alps	231–1,696 km^2 (0–22%)	Winter runoff (increase at high elevations)	Transition of snowfall to rainfall	1980–2009 to 2020–2049, 2045–2074, 2070–2099	10 GCM-RCMs	RCP2.6, SRES A1B, A2	Addor et al. (2014)
European Alps	(glacierized)	Annual runoff (decrease)	Decreased glacier melt	1980–2009 to 2010–2039, 2040–2069, 2070–2099	4 GCMs	RCP2.6, RCP4.5, RCP8.5	Farinotti et al. (2016)
〃	〃	Summer runoff (decrease)	Decreased glacier melt	〃	〃	〃	〃
Alps, Po (Italy)	71,000 km^2 (small)	Winter runoff (increase)	Transition of snowfall to rainfall	1960–1990 to 2020–2050	2 RCMs	SRES A1B	Coppola et al. (2014)
〃	〃	Spring peak (1 month earlier)	Earlier snowmelt	〃	〃	〃	〃
Canton Graubünden	7,214 km^2 (2.4%, ~20% in high elevation catchments)	Winter runoff (increase)	Transition of snowfall to rainfall	2000–2010 to 2021–2050, 2070–2095	10 RCMs	SRES A1B	Bavay et al. (2013)
〃	〃	Summer runoff (decrease)	Decreased snowmelt, decreased precipitation	〃	〃	〃	〃
〃	〃	Spring peak (earlier)	Earlier snowmelt	〃	〃	〃	〃
Göscheneralpsee, Dammareuss subcatchment (central Switzerland)	95 km^2 (20%), 10 km^2 (50%)	Summer runoff (decrease)	Decreased snow melt, decreased glacier melt	1981–2010 to 2021–2050, 2070–2099	10 RCMs	SRES A1B	Kobierska et al. (2013)
Findelen, Swiss Alps	21.18 km^2 (70%)	Annual runoff (decrease)	Decreased glacier melt	1976–2086	1 RCM	SRES A2	Uhlmann et al. (2013)
〃	〃	Spring peak (earlier)	Earlier snowmelt	〃	〃	〃	〃

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Location	Basin area (% glacier cover)	Variable (change)	Cause	Time period	Method	Scenario	Reference
Scandinavia							
Arctic coastal Norway	56–422 km^2 (0–34.9%), no data in some basins	Winter runoff (increase)	Transition of snowfall to rainfall	1955–2010, depending on sites	7 stream gauges	Past	Fleming and Dahlke (2014)
"	"	Summer runoff (decrease basins including glaciers)	Decreased glacier melt	"	"	"	"
Whole Scandinavia	(including glaciers)	Winter runoff increase ~40%, excluding southern Sweden and Denmark)	Transition of snowfall to rainfall	1980–2009 to 2041–2070	6 GCM-RCMs	SRES A1B	Räty et al. (2017)
"	"	Summer runoff (decrease ~40%)	Decreased snowmelt, increased evapotranspiration	"	"	"	"
Caucasus and Middle East							
Eastern Anatolia (Turkey)	(0%)	Snowmelt peak (~1 week earlier)	Earlier snowmelt	1970–2010	15 stream gauges	Past	Yucel et al. (2015)
"	"	Snowmelt peak (~4 weeks earlier)	Earlier snowmelt	1961–1990 to 2070–2099	Single GCM-RCM	SRES A2	"
Euphrates-Tigris	880,000 km^2 (0%)	Snowmelt peak (18–39 days earlier)	Earlier snowmelt	1961–1990 to 2041–2070, 2071–2099	3 GCM-RCMs	SRES A1F1, A2, B1	Bozkurt and Sen (2013)
Low Latitudes (tropical Andes)							
La Paz (Bolivia)	18–78 km^2 (5–12%)	Annual runoff (no significant change)	Decreased ice melt compensated by increased precipitation	1963–1007	4 stream gauges and model	Past	Soruco et al. (2015)
Zongo (Bolivia)	3 km^2 (35% in 1987)	Annual runoff (-4% and -24% in later period)	Decreased glacier melt	1987–2010 to 2030–2050, 2080–2100	Downscaled 11 GCMs	RCP4.5	Frans et al. (2015)
"	"	Wet season runoff (increase)	Transition of snowfall to rainfall	"	"	"	"
Southern Andes							
Elqui (Chile)	222–3,572 km^2 (7.02 km^2 in total)	Annual runoff (no significant change)	Decreased glacier melt compensated by increased precipitation	1970–2009	4 stream gauges	Past	Balocchi et al. (2017)
Rio del Yeso (Andes of central Chile)	62 km^2 (19%)	Annual runoff (decrease)	Decreased snowmelt	2000–2015	Model	Past	Burger et al. (2019)
Juncal (Chile)	(including glaciers)	Seasonal runoff peak (1month earlier)	Earlier snowmelt, transition of snowfall to rainfall	2001–2010 to 2041–2050, 2051–2060, 2060–2100	12 GCMs	RCP4.5, RCP8.5	Ragettli et al. (2016)
High Mountain Asia							
Astore, Gilgit, Katchura, (upper Indus)	3,750 km^2, 12,800 km^2, 115,289 km^2, (not significant)	Spring and summer runoff (increase)	Increased snowmelt, transition of snowfall to rainfall	1970–2005	Stream gauge	Past	Reggiani and Rientjes (2015)
Hunza, (upper Indus)	13,925 km^2 (including glaciers)	Spring and Summer runoff (decrease)	Decreased glacier melt	"	"	"	"
Naryn (Tien Shan)	3,879 km^2 (10% in 1970s) and 5,547 km^2 (12% in 1970s)	Spring and autumn runoff (increase)	Increased snowmelt and ice melt	1965–2007	2 stream gauges	Past	Kriegel et al. (2013)
"	"	Winter-early spring runoff (increase)	Increased snowmelt, transition of snowfall to rainfall	"	"	"	"
Tien Shan	(including glaciers)	Annual runoff (increase for higher fraction of glacier area)	Increased ice melt	1960–2014	23 stream gauges	Past	Chen et al. (2016)

Location	Basin area (% glacier cover)	Variable (change)	Cause	Time period	Method	Scenario	Reference
Toxkan, Kunmalik, Kaidu, Huangshuigou (Tien Shan)	4,298–19,166 km^2 (including glaciers)	Winter-spring runoff (increased, earlier)	Earlier snow and glacier melt	1961–2008, depending on site	4 stream gauges	Past	Shen et al. (2018)
Kakshaal and, Tarim	18,410 km^2 (4.4%)	Summer runoff (increase)	Increased ice melt, increased precipitation	1957–2004	Model	Past	Duethmann et al. (2015)
Sari-Djaz, Tarim	12,948 km^2 (20.9%)	Summer runoff (increase)	Increased ice melt	〃	〃	〃	〃
Shigar (Karakoram)	7,040 km^2 (30%)	June and July runoff (increase and turn to decrease from 2000–2010)	Decreased snowmelt	1985–2010	Stream gauges, hydrograph separation	Past	Mukhopadhyay and Khan (2014)
〃	〃	August runoff (increase)	Increased glacier melt	〃	〃	〃	〃
Chhota Shigri (Western Himalaya)	~35 km^2 (46.5%)	Summer runoff (14–22%)	Increased glacier melt	1955–1969 to 1970–1984, 1985–1999, 2000–2014	RCM and mass-balance model	Past	Engelhardt et al. (2017)
Sikeshu (Tien Shan)	921 km^2 (37%)	Annual runoff (increase)	Increased glacier melt	1964–2004	1 stream gauge	Past	Wang et al. (2015)
Upper Indus	~425,000 km^2 (5%)	June and July runoff in lower elevations (decrease)	Decreased snowmelt, decreased precipitation	1971–2000 to 2071–2100	4 GCM-RCMs	RCP4.5, RCP8.5	Lutz et al. (2016a)
〃	〃	Winter runoff in lower elevation (increase)	Increased precipitation, transition of snowfall to rainfall	〃	〃	〃	〃
〃	〃	Spring peak (earlier)	Earlier snow and glacier melt	〃	〃	〃	〃
Chu (Tien Shan)	9,548 km^2 (2–7%)	Annual runoff (–27.7 to -6.6%)	Decreased glacier melt	1966–1995 to 2016–2045, 2066–2095	5 GCMs	RCP2.6, RCP4.5, RCP8.5	Ma et al. (2015)
〃	〃	Spring peak (decrease, 1 month earlier)	Decreased glacier melt, earlier snowmelt	〃	〃	〃	〃
Upper basin of Indus, Brahmaputra, Ganges, Salween, Mekong	(0.2–5.4%)	Spring peak (decrease, earlier)	Earlier snowmelt, transition of snowfall to rainfall	1998–2007 to 2041–2050	4 GCMs	RCP4.5, RCP8.5	Lutz et al. (2014)
Naryn (Tien Shan)	58,205 km^2 (2%)	Annual runoff (decrease)	Decreased precipitation, decreased snowmelt	1966–1995 to 2016–2045, 2066–2095	5 GCMs	RCP2.6, RCP4.5, RCP8.5	Gan et al. (2015)
〃	〃	Winter runoff (–2.2 to 19.8%)	Decreased precipitation, decreased snowmelt	〃	〃	〃	〃
〃	〃	Spring peak (1 month earlier)	Earlier snowmelt	〃	〃	〃	〃
Chon Kemin (Kyrgyz-Kazakh region)	1,037 km^2 (11%)	Summer runoff (-15 to -4%, -66 to -9%)	Decreased ice melt	1955–1999 to 2000–2049, 2050–2099	4 GCMs	RCP2.6, RCP8.5	Sorg et al. (2014a)
〃	〃	Spring runoff (7–23%, 18–62%)	Increased winter precipitation, increased snowmelt	〃	〃	〃	〃
Beida River, upper Heihe (China)	565–6,706 km^2 (total 318.2 km^2)	Annual runoff (increase)	Increased glacier melt	1957–2013	3 stream gauges	Past	Wang et al. (2017b)
Lhasa, upper Brahmaputra	32,800 km^2 (2% in 1970, 1.3–11.5% for selected sub-basins)	Early summer runoff (decrease)	Decreased snowmelt, increased evapotranspiration	1971–2000 to 2011–2040, 2051–2080	Single GCM-RCM	SRES A1B, A2, B2	Prasch et al. (2013)
Koshi (Nepal)	3,712 km^2 (13%)	Summer runoff (decrease)	Decreased snow melt	2000–2010 to 2040–2050, 2086–2096	5 GCM-RCMs	SRES A1B	Nepal (2016)

Location	Basin area (% glacier cover)	Variable (change)	Cause	Time period	Method	Scenario	Reference
Upper Langtang (Himalaya)	(including glaciers)	Peak runoff (increase)	Transition of snowfall to rainfall	2001–2010 to 2041–2050, 2051–2060, 2060–2100	12 GCMs	RCP4.5, RCP8.5	Ragettli et al. (2016)
Langtang (Himalaya)	360 km^2 (46%)	Annual runoff (increase)	Increased glacier melt	1961–1990 to 2021–2050, 2071–2100	8 GCMs	RCP4.5, RCP8.5	Immerzeel et al. (2013)
Baltoro	1,415 km^2 (46%)	Annual runoff (increase)	Increased glacier melt		"	"	"
Chhota Shigri (Western Himalaya)	~35 km^2 (46.5%)	Spring-summer runoff (increase)	Earlier snow and glacier melt	1951–2099 to 2070–2099	GCM-RCM	RCP4.5, RCP8.5	Engelhardt et al. (2017)
"	"	Summer runoff (decrease)	Decreased glacier melt	"	"	"	"
Hunza, upper Indus (Western Himalaya)	13,567 km^2 (including glaciers)	Spring runoff (increase, earlier in 2 GCMs, decrease in 1 GCM)	Early snow melt	1980–2010 to 2030–2059, 2070–2099	3 GCMs	RCP2.6, RCP8.5	Garee et al. (2017)
"	"	Summer runoff (decrease in 2 GCMs, slight increase in 1 GCM)	Decreased glacier melt	"	"	"	"
New Zealand and SE Australia							
Upper Waitaki (New Zealand)	9,490 km^2 (including glaciers)	Late winter-spring runoff (increase)	Transition of snowfall to rainfall	1980–1999 to 2030–2049, 2030–2049, 2080–2099	Downscaled 12 GCMs	SRES A1B	Caruso et al. (2017)
"	"	Summer runoff (decrease)	Decreased snowmelt, decreased precipitation	"	"	"	"
Other regions (affected by snow cover but lacking glaciers)							
Eastern Scotland	749 km^2 (0%)	Winter runoff (increase)	Transition of snowfall to rainfall, precipitation increase	1960–1991 to 2010–2039, 2030–2059, 2070–2099	11 RCMs	SRES A1F1, A1B, B1	Capell et al. (2014)
Shubuto, Hokkaido (Japan)	367.1 km^2 (0%)	Spring peak (~14 days earlier)	Earlier snowmelt	2046–2065	5 GCMs	SRES A1B	Bhatti et al. (2016)

SM2.7 Details of Studies on Peak Water

Table SM2.10 | Overview of studies providing estimates of the timing of peak water for the individual glaciers or glacier-fed river basins plotted in Figure 2.6. Peak water is the approximate year derived from observations or modelling (past) and modelling (future) when on average annual runoff reaches a maximum due to glacier shrinkage. Years are approximated from the information presented in each study, and in some cases represent an average of results from different scenarios (see remarks). *Local* refers to estimates for individual glaciers (no matter glacier area) and river basins with multiple glaciers but total glacier cover less than 150 km^2. All other estimates are referred to as *regional.* Glacier area refers to reported area typically referring to the beginning of the study period. Glacier cover refers to the glacier area in percent of the river basin's area.

Glacier/basin name	Domain type	Peak water (year)	Glacier area (km^2)	Glacier cover (%)	Reference	Remarks; scenario (if reported)
Alaska						
Copper River basin	regional	~2070	~13,000	~21	Valentin et al. (2018)	RCP4.5
Wolverine	local	~2050	17	67	Van Tiel et al. (2018)	No clear peak; RCP4.5
Wolverine	local	~2035	17	67		No clear peak; RCP8.5
Western Canada						
Hood	local	~2015	~9	100	Frans et al. (2016)	Runoff from glacier area
Bridge	local	~2015	73	53	Moyer et al. (2016)	Qualitative statement: At/close to peak water
Mica basin	regional	~2000	1,080	52	Jost et al. (2012)	Already past peak water; year not reported
Bridge	local	~2000	73	53	Stahl et al. (2008)	Already past peak water; year not reported

Glacier/basin name	Domain type	Peak water (year)	Glacier area (km^2)	Glacier cover (%)	Reference	Remarks; scenario (if reported)
Hoh	local	1988	18	100	Frans et al. (2018)	Runoff from glacier area; RCP4.5
Stehekin	local	1985	19	100		
Cascade	local	1984	12	100		
Hood	local	1995	5	100		
Thunder	local	2040	32	100		
Nisqually	local	2053	18	100		
Several basins in Western Canada	regional	~2000	150		Fleming and Dahlke (2014)	"Peak Water already over" (qualitative statement); runoff data analysis
Western Canada, coastal Alaska	regional	~2035	26,700	100	Clarke et al. (2015)	Runoff from glacier area; Peak water varying between ~2023 and 2055; RCP2.6
Western Canada, coastal Alaska	regional	~2042	26,700	100		Runoff from glacier area; Peak water varying between ~2024 and 2065; RCP8.5
Iceland						
Southern Vatnajökull, Langjökull, Hofsjökull	local/ regional	~2055	~5,000	100	Björnsson and Pálsson (2008)	
Central Europe (European Alps)						
Gries	local	2020	5	49	Farinotti et al. (2012)	A1B
Silvretta	local	2015	5	5		
Rhone	local	2042	18	46		
Gorner	local	2035	51	63		
Aletsch	local	2050	117	59		
Trift	local	2045	17	43		
Zinal	local	2047	11	65	Huss et al. (2008)	A1B
Moming	local	2039	6	63		
Weisshorn	local	2035	3	39		
Morteratsch	local	2020	16	15	Huss et al. (2010)	A1B
Forno	local	2042	7	34		
Albigna	local	2020	6	30		
Plaine Morte	local	2055	8	100	Reynard et al. (2014)	A1B
Findel	local	2035	16	74	Uhlmann et al. (2013)	
Findel	local	~2050	16	74	Huss et al. (2014)	A1B (Peak water 2035–2065 depending on climate model
Swiss Alps	local (>100 glaciers)	1997	<0.05	100	Huss and Fischer (2016)	
Swiss Alps		2000	0.05–0.125	100		
Swiss Alps		2004	0.125–0.5	100		
High Mountain Asia						
Chon Kemin basin	regional	~2045	112	11	Sorg et al. (2014a)	RCP2.6
Chon Kemin basin	regional	~2025	112	11		RCP8.5
Largest rivers of China	regional	~2070	~30,000		Su et al. (2016)	Peak water unclear from study; RCP2.6
Largest rivers of China	regional	~2070	~30,000			Peak water unclear from study; RCP8.5
Hailuogou	local	~2050	45	36	Zhang et al. (2015)	No clear peak; declining glacier runoff after 2050; RCP4.5
Hailuogou	local	~2070	45	36		RCP8.5
Kakshaal basin	regional	~2018	740	4	Duethmann et al. (2016)	Runoff from glacier area; aggregate of different emission scenarios; RCP2.6/RCP8.5
Sari-Djaz basin	regional	~2033	2,580	20		

Glacier/basin name	Domain type	Peak water (year)	Glacier area (km^2)	Glacier cover (%)	Reference	Remarks; scenario (if reported)
Naryn basin	regional	~2020	1,160	2	Gan et al. (2015)	RCP2.6
Naryn basin	regional	~2030	1,160	2		RCP4.5
Naryn basin	regional	~2050	1,160	2		RCP8.5
Urumqi	local	2020	2	52	Gao et al. (2018)	RCP4.5
Yangbajing basin	regional	~2025	312	11	Prasch et al. (2013)	Peak water between 2011 and 2040; A1B
Headwaters of Brahmaputra, Ganges, Indus	regional	~2050	~30,000		Lutz et al. (2014)	RCP4.5
All High Mountain Asia glaciers	regional	~2030	~90,000	100	Kraaijenbrink et al. (2017)	RCP4.5
All High Mountain Asia glaciers	regional	~2050	~90,000	100		RCP8.5
Chhota Shigri	local	2040	16	46	Engelhardt et al. (2017)	No clear peak; RCP4.5
Chhota Shigri	local	2020	16	46		No clear peak; RCP8.5
Hypothetical	local	2055	50	1	Rees and Collins (2006)	Runoff from glacier area
Hypothetical	local	2064	50	1		
Langtang	local	2045	120	100	Immerzeel et al. (2013)	RCP4.5
Baltoro	local	2048	520	100		RCP8.5
Langtang	local	2044	120	100		RCP4.5
Baltoro	local	2065	520	100		RCP8.5
Langtang	local	~2055	120	34	Ragettli et al. (2016)	RCP4.5
Langtang	local	~2070	120	34		RCP8.5
Low Latitudes (Andes)						
Rio Santa basin	regional	~2005	200	2	Carey et al. (2014)	"Peak water already over" (qualitative statement)
Zongo	local	2010	3	21	Frans et al. (2015)	
Cordillera Blanca	regional	~1995	480		Polk et al. (2017)	"Peak water already over" (qualitative statement)
Sub-basins of Rio Santa		~1990	200	2	Baraer et al. (2012)	Analysis of observations
Scandinavia						
Nigardsbreen	local	~2080	45	70	Van Tiel et al. (2018)	No clear peak; RCP4.5
Nigardsbreen	local	~2080	45	70		No clear peak; RCP8.5
Southern Andes						
Juncal	local	2030	34	14	Ragettli et al. (2016)	RCP4.5
Juncal	local	2020	34	14		RCP8.5

SM2.8 Details of Studies on Observed Impacts Attributed to Cryosphere Changes

Table SM2.11 | Overview of studies documenting observed impacts on ecosystems, other natural systems and human systems over the past several decades that can at least partly be attributed to changes in the cryosphere, per high mountain region (as defined in Figure 2.1). Other additional climatic or non-climatic drivers are not listed. 'Attribution Confidence' refers to the strength of the evidence in attributing the impact to cryosphere changes (H for high, M for medium, L for low). Only studies where the 'Attribution Confidence' is at least medium are listed. Also listed whether or not the impact is positive (pos), neg (neg) or mixed for the impacted system. Figure 2.8 is based on the data provided in this table.

Location	Affected sector or system	Impact	Cryosphere change	Attribution confidence	Positive/ negative/ mixed	Reference
Alaska						
Alaska	Landslides	Increase in frequency of large rock avalanches	Permafrost degradation	M	neg	Coe et al. (2017)
Alaska	Terrestrial ecosystems (tundra)	Population performance of a large mammal (dall sheep)	Spring snow cover	M	mixed	van de Kerk et al. (2018)
Alaska	Terrestrial ecosystems (tundra; forest)	Decline in abundance & offspring recruitment of a large mammal (mountain goat)	Harsh winter conditions (extreme weather events); delayed spring onset/end of snow season	M	neg	Rattenbury et al. (2018)
Alaska	Culture, Tourism	Route change for Iditarod dog-sled race	Insufficient snow cover, lack of river/lake ice	H	neg	Hagenstad et al. (2018)
Western Canada and USA						
British Columbia	Hydropower	Change in runoff timing	Reduction in peak winter snow accumulation, glacier decline	H (snow) M (glacier)	mixed	Jost et al. (2012); Jost and Weber (2013)
Sacramento River basin, California	Hydropower	Change in runoff timing	Reduced snowpack due to more precipitation as rain	H	neg	Van Lienden et al. (2014)
San Joaquin River basin, California	Hydropower	Change in runoff timing	Reduced snowpack due to more precipitation as rain	M	neg	Van Lienden et al. (2014)
Upper Colorado River, USA	Hydropower	Change in runoff timing	Earlier snowmelt runoff	H	neg	Kopytkovskiy et al. (2015)
British Columbia	Landslides	Increase in landslide frequency	Glacier retreat and loss	M	neg	Cloutier et al. (2017)
Entire Western USA	Floods	Decrease in frequency of rain-on-snow flood event at lower elevation	Decrease in duration and depth of snow cover	M	pos	McCabe et al. (2007)
Entire Western USA	Floods	Increase in frequency of rain-on-snow flood event at higher elevation	Increase in frequency of rainfall at high elevation in winter	M	neg	"
Canada/USA	Terrestrial ecosystems (tundra; forest)	Population dynamics of wolverines and other mammals and birds	Winter snowpack decline and temperature anomalies	H	mixed	Brodie and Post (2010); Zimoval et al., (2018)
Colorado Rocky Mountains	Terrestrial ecosystems (tundra)	Changes in vegetation distribution (shrub and tundra expansion)	Spring snow cover (snow water equivalent)	M	pos	Bueno de Mesquita et al. (2018)
Mid-elevation Northern Rocky Mountains	Terrestrial ecosystems (forest)	Fire extent, fire season severity, and fire season duration increase	Earlier spring snowmelt	M	neg	Westerling (2016)
Colorado Rocky Mountains	Terrestrial ecosystems (tundra)	Changing upper and lower boundaries of alpine tundra, and within plant community shifts	Snow changes	M	mixed	Suding et al. (2015)
Cascade Mountains	Terrestrial ecosystems (tundra)	Change in abundance of a small mammal (pika) at different elevations	Record low snowpack (snow drought)	H	mixed	Johnston et al. (2019)
Colorado Rocky Mountains	Terrestrial ecosystems (subalpine meadows)	Decrease in peak season net ecosystem production	Earlier snowmelt, longer early season drought	M	neg	Sloat et al. (2015)

Location	Affected sector or system	Impact	Cryosphere change	Attribution confidence	Positive/ negative/ mixed	Reference
Montana	Freshwater ecosystems	Loss of endemic invertebrates strongly dependent on glacier water fed habitats	Decreased glacier runoff due to glacier decline	M	neg	Giersch et al. (2017) Muhlfeld et al. (2011)
Rocky Mountains	Freshwater ecosystems	Cutthroat trout and bull trout range reduced	Decreased glacier runoff due to glacier decline	M	neg	Young et al. (2018)
Western USA and Western Canada	Tourism	Reduced operating capabilities of ski resorts	Less snow	H	neg	Steiger et al. (2017); Hagenstad et al. (2018)
Cascades, USA	Tourism	Reduced ice-climbing opportunities and reduced attractions for summer trekking	Glacier retreat	M	neg	Orlove et al. (2019)
Iceland						
Sandá í Þistilfirð, Iceland	Hydropower	Change in timing of input	Change in seasonality of snowmelt	M	neg	Einarsson and Jónsson (2010)
Austari-Jökulsá, Iceland	Hydropower	Change in timing of input	Change in seasonality of snowmelt and glacier decline	M	neg	Einarsson and Jónsson (2010)
Northern Iceland	Landslides	Large debris slide	Deep thawing of ground ice	H	neg	Sæmundsson et al. (2018)
Iceland	Freshwater ecosystems	Change in species interactions and loss of taxa	Decreased runoff due to glacier decline	M	neg	Milner et al. (2017)
Jokulsarlon	Tourism	Glacier-based tourism	Positive effect – picturesque glacial lagoon formed by glacier retreat	H	pos	Þórhallsdóttir and Ólafsson (2017)
Central Europe						
European Alps	Water quality	Increased heavy metal concentrations in lakes	Release of solutes from thawing permafrost	M	neg	Thies et al. (2007)
European Alps	Water quality	Increased heavy metal concentrations in lakes	Release of solutes from thawing permafrost	M	neg	Ilyashuk et al. (2018)
European Alps	Water quality	Increased heavy metal concentrations in streams	Release of solutes from thawing permafrost	M	neg	Thies et al. (2013)
Carpathians, Eastern Europe	Hydropower	Reduced water inflow in input due to change in runoff timing	Reduction of perennial snowpacks and earlier snowmelt – reduced input and change in seasonality of input	M	neg	Alberton et al. (2017)
Löntsch, Switzerland	Hydropower	Increase in runoff (short-term)	Slight glacier decline	M	pos	Hänggi and Weingartner (2011) Weingartner et al., (2013)
Löntsch, Switzerland	Hydropower	Change in runoff and timing	Snow cover – slightly more precipitation/snow, slightly less snow cover, slight increase in snowmelt	M	mixed	"
Oberhasli, Switzerland	Hydropower	Change in timing of runoff	Glaciers – significant reduction, decrease of glacier melt with slightly earlier maximum	M	neg	Weingartner et al. (2013)
Göscheneralp reservoir, Switzerland	Hydropower	Change in timing of input	Snow cover – minor change of seasonality	M	-	"
Gougra, Switzerland	Hydropower	Increase in input	Glaciers – significant reduction, increase in runoff	M	pos	"
Gougra, Switzerland	Hydropower	Change in timing of input	Snow cover – change in timing of runoff	M	neg	"
Switzerland	Hydropower	Increased water inflow	Glacier retreat	H	pos	Schaefli et al. (2019)
Italian Alps	Hydropower	Decreased water supply for run-of-river hydropower	Glacier retreat has reduced summer runoff	M	neg	Orlove et al. (2019)

Location	Affected sector or system	Impact	Cryosphere change	Attribution confidence	Positive/ negative/ mixed	Reference
French and Italian Alps	Landslides	Increase in rock avalanche frequency	Glacier retreat and permafrost degradation	M	neg	Ravanel and Deline (2011); Fischer et al. (2012); Ravanel et al. (2017)
Swiss Alps	Landslides	Increase in frequency of large debris flows	Permafrost degradation	M	neg	Stoffel and Graf (2015)
European Alps	Landslides	Rock glacier destabilisation	Permafrost thaw	H	neg	Roer et al. (2008)
European Alps	Landslides	Increasing debris flows and small rock fall	Permafrost thaw	H	neg	Kummert et al. (2017)
European Alps	Landslides	Rock glacier collapse	Permafrost thaw	H	neg	Bodin et al. (2016)
European Alps	Landslides	Increasing rockfall during heat waves	Permafrost thaw	H	neg	Ravanel et al. (2017)
European Alps	Landslides	Increasing rockfall	Permafrost thaw	H	neg	Ravanel et al. (2010)
European Alps	Landslides	Increasing rockfall during recent decades	Permafrost thaw	M	neg	Ravanel and Deline (2011)
Swiss Alps	Landslides	Increase in debris transport into steep slopes and destabilisation of rock glaciers	Permafrost degradation	M	neg	Kääb et al. (2007)
European Alps	Snow avalanche	More avalanches involving wet snow	Changes in snow cover characteristics	M	neg	Pielmeier et al. (2013) Naaim et al. (2016)
European Alps	Snow avalanche	Decrease in total number of avalanches at lower elevation	Changes in snow cover characteristics	M	pos	Eckert et al. (2013); Lavigne et al. (2015)
Tatras mountains	Snow avalanche	Decline in mass and intensity of large avalanches	Changes in snow cover characteristics	M	pos	Gadek et al. (2017)
European Alps	Floods	Decrease in rain on snow flood event at lower elevation and in spring	Change in duration and depth of snow cover and change in precipitation type (rain compared to snow)	M	pos	Freudiger et al. (2014); Moran-Tejéda et al. (2016)
European Alps	Floods	Increase in rain on snow flood event at higher elevation and in winter	Change in duration and depth of snow cover and change in precipitation type (rain vs. snow)	M	neg	"
Poland (Białowieża Forest)	Terrestrial ecosystems	Increased predation pressure in a mammal (weasel) due to phenological camouflage mismatch	Decreasing number of snow cover days	M	neg	Atmeh et al. (2018)
Pyrenees	Terrestrial ecosystems	Availability duration of high quality food for a bird (ptarmigan)	Earlier snowmelt	M	pos	García-González et al. (2016)
Swiss Alps	Terrestrial ecosystems (tundra)	Alpine grassland species colonize the snowbeds	Shorter snow cover duration	M	mixed	Matteodo et al. (2016)
Italian Alps	Terrestrial ecosystems (tundra)	Soil and plant community development can be very slow under some soil/bedrock conditions (serpentinite)	Glacier retreat	H	mixed	D'Amico et al. (2017)
French Pyrenees	Freshwater ecosystems	Increased local diversity; decreased regional diversity	Decreased runoff due to glacier decline	H	mixed	Khamis et al. (2016)
French Pyrenees	Freshwater ecosystems	Reduction in genetic diversity	Decreased runoff due to glacier decline	M	neg	Finn et al. (2013)
Swiss Alps	Freshwater ecosystems	Upward shift of invertebrate communities as hydrological regime and water temperatures change	Glacier retreat	H	mixed	Finn et al. (2010)
Italian Alps	Freshwater ecosystems	Loss of endemic invertebrates	Decreased runoff due to glacier decline	H	neg	Lencioni (2018)
Western Balkans	Freshwater ecosystems	Loss of native trout	Decreased runoff due to glacier decline	M	neg	Papadaki et al. (2016)
Austrian Alps	Freshwater ecosystems	Increased diatom biodiversity	Decreased runoff due to glacier decline	M	pos	Fell et al. (2018)

Location	Affected sector or system	Impact	Cryosphere change	Attribution confidence	Positive/ negative/ mixed	Reference
European Alps	Infrastructure	Structure instability	Permafrost thaw	M	neg	Phillips and Margreth (2008)
European Alps and Pyrenees	Tourism	Reduction in ski lift revenues and operating capabilities of ski resorts	Reduction of snow cover duration	H	neg	Steiger et al. (2017)
European Alps	Tourism	Changes in the safety of mountaineering routes	Glacier decline, permafrost thaw (impact on ground instability)	H	neg	Ritter et al. (2012); Duvillard et al. (2015); Ravanel et al. (2017); Mourey et al. (2019)
Italian Alps	Culture	Aesthetic quality; Local residents find the dark peaks in summer to be unattractive	Glacier retreat	H	neg	Brugger et al. (2013)
Italian Alps	Culture	Local residents feel that the identity of their village is weakening as the peaks have less ice and snow	Reduced ice and snow cover	H	neg	Jurt et al. (2015)
Scandinavia/Nordic						
Northern Norway	Hydropower	More water for hydropower	Thinning of glacier, changed routing of glacier-dammed lake	H	pos	Engeset et al. (2005)
Northern Norway	Landslides	Increase in debris transport into steep slopes	Increase in rock glacier speed	M	neg	Eriksen et al. (2018)
Norway	Terrestrial ecosystems (tundra; forest)	Increased mortality from predation of a small mammal species (mountain hare) due to camouflage mismatch	Snow cover duration	H	neg	Pedersen et al. (2017)
Norway	Terrestrial ecosystems (tundra)	Invertebrate, plant and fungal communities develop during primary succession	Glacier retreat	H	pos	Matthews and Vater (2015)
Finland	Tourism	Reduction in ski lift revenues	Reduced snow cover duration	M	neg	Falk and Vieru (2017)
Caucasus and Middle East						
Central Caucasus	Snow avalanche	Increased risk of large avalanches	Glacier decline, change in snow conditions	M	neg	Aleynikov et al. (2011) Volodicheva et al. (2014)
Central Caucasus	Floods	Increased risk of outburst floods	Glacier decline, permafrost thaw (impact on ground instability)	M	neg	Petrakov et al. (2012) Chernomorets et al. (2018)
Western Caucasus	Tourism	Ski tourism	Reduction of snow cover duration	M	neg	Sokratov et al. (2014)
North Asia						
Russia (Altai mountains)	Terrestrial ecosystems (tundra)	Soil properties, plant, fungi and microbial communities develop during primary succession	Glacier retreat	H	mixed	Cazzolla Gatti et al. (2018)
Southern Andes						
Central Chile	Water resources	Reduced water supply reserves	Reduction and melt/collapse of rocky glaciers	L/M	neg	Navarro et al. (2018)
Patagonia	Glacier lakes	Increase in size and number of glacier lakes; risk of outburst floods (e.g., at new locations)	Glacier decline	H	neg	Navarro et al. (2018); Wilson et al. (2018) Colavitto et al. (2012)
Central Chile	Floods	Increase in maximum annual flow	Snow and glacier melt, shifts in peak flow (increasing)	M	neg	Pizarro et al. (2013)
Chilean and Argentinean Andes	Floods	Increase in GLOF frequency, partially due to glacier shrinkage and lake growth	Glacier decline	M	neg	Anacona et al., (2015a)
Chile	Agriculture	Increased water availability for irrigation and agricultural yields	Increased runoff due to more glacier melt	M	pos	Young et al. (2010)
Chilean Patagonia	Freshwater ecosystem	Spawn rates for certain fish species negatively affected (some of great commercial value for the region)	Changes in water temperature and salinity due to changing ice and snow melt	L/M	neg	Landaeta et al. (2012)

Location	Affected sector or system	Impact	Cryosphere change	Attribution confidence	Positive/ negative/ mixed	Reference
Low Latitudes						
Cordillera Blanca, Peruvian Andes	Water resources	Drinking water supply in rural areas	Reduced glacier contribution to groundwater which maintains springs	H	neg	Baraer et al. (2012)
Peruvian Andes	Agriculture	Negative impact on crops, pastures and livestock	Reduced runoff due to glacier retreat	M	neg	Mark et al. (2010); Bury et al. (2011)
Central Andes (Bolivia, Peru)	Terrestrial ecosystems (tundra)	Constrained plant primary succession	Glacier retreat	M	neg	(Zimmer et al., 2018)
Northern Andes (Ecuador)	Terrestrial ecosystems (tundra)	Upward shifts of vegetation zones and maximum elevation of species	Glacier retreat	L/M	pos	Morueta-Holme et al. (2015)
Ecuador	Freshwater ecosystems	Decrease in regional biodiversity	Reduced runoff due to glacier decline	M	neg	Milner et al. (2017)
Ecuador	Freshwater ecosystems	Downstream shift of macro-invertebrates	Reduced runoff due to glacier decline	M	pos	Jacobsen et al. (2014)
Tropical Andes	Tourism	Closure of a ski resort	Glacier disappearance, reduced snow cover	H	neg	Kaenzig et al. (2016)
Peruvian Andes	Culture	Spiritual value: concern among local residents who seek to restore relations with the local mountain deity	Glacier retreat and lesser snowmelt on a major mountain have reduced flow in a river	H	neg	Stensrud (2016)
Ecuadorian Andes	Culture	Loss of indigenous knowledge, especially among youth and children, in a setting where such knowledge is closely linked to the physical presence of the glacier	Glacier decline and disappearance	M	neg	Rhoades et al. (2008)
Peruvian Andes	Culture	Spiritual value: the site of a major pilgrimage was altered, making it more difficult for pilgrims to access the site, and creating distress and concern for them	Glacier retreat	H	neg	Allison (2015)
Peruvian Andes	Migration	Emigration and increased wage labour migration: Glacier runoff used to irrigate pasture, so herders increased their temporary migration for wage labour opportunities; the greater propensity of younger adults to migrate alters the demographic composition of the herding community, with a larger proportion of elderly and female than previously	Reduced runoff due to glacier retreat and lesser snowmelt runoff	M	neg	Alata et al. (2018)
Bolivian Andes	Migration	Increased emigration and declines in the productivity of irrigated agriculture	Reduced runoff due to glacier retreat	M	neg	Brandt et al. (2016)
High Mountain Asia						
Nepal	Water resources	Drinking water supply in rural areas reduced	Glacier retreat and reduced snow cover	M	neg	McDowell et al. (2013)
Several regions	Hydropower	More/less water for hydropower depending on timing for different regions	Increased/decreased runoff due to glacier decline and change in snowpack	H	mixed	Lutz et al. (2016b)
Gilgit-Baltistan, Pakistan	Agriculture	Reduced water availability for irrigation of crops on a major mountain	Reduced runoff due to glacier retreat and less snowmelt	H	neg	Nüsser and Schmidt (2017)
Nepal	Agriculture	Reduction in quality of pasture, which reduces the capacity of the area to support livestock	Reduced snow cover duration	M	neg	Shaoliang et al. (2012)
Nepal	Agriculture	Decreased agricultural production	More erratic snowfall	M	neg	Gentle and Maraseni (2012)
Nepal	Agriculture	Less favourable potato planting conditions	Seasonally delayed snowfall	M	neg	Sujakhu et al. (2016)
Nepal	Agriculture	Reduced soil moisture, which reduces crop yield	Reduced snow cover	M	neg	Prasain (2018)
Pakistan	Agriculture	Irrigation	Reduced runoff due to glacier retreat	M	neg	Nüsser and Schmidt (2017)

Location	Affected sector or system	Impact	Cryosphere change	Attribution confidence	Positive/ negative/ mixed	Reference
Nepal	Agriculture	Reduced yields due drying of soils in winter and reduced moisture input in spring	Reduced snow cover	M	neg	Smadja et al. (2015)
Himalaya	Snow avalanche	Increase in occurrence of avalanches	Change in snow conditions (more wet snow conditions)	M	neg	Ballesteros-Cánovas et al. (2018)
Himalaya	Glacier lakes	Increase in size and number of glacier lakes	Glacier retreat	H	mixed	Frey et al. (2010); (Gardelle et al., 2011)
Himalaya	Glacier lakes	Risk of outburst floods (e.g., at new locations)	Glacier retreat led to increase in number and size of glacier lakes	H	neg	Carrivick and Tweed (2016); Harrison et al. (2018); Veh et al. (2019)
Himalaya	Glacier lakes	Increased exposure of (growing) tourism/pilgrims to glacier lake outburst floods	Glacier retreat and lake formation	H	neg	Uniyal (2013)
Himalaya	Glacier lakes	Increase in exposure of hydropower plants to glacier lake outburst floods	Glacier retreat and lake formation	M	neg	Schwanghart et al. (2016)
China (Tibetan plateau, Hailuogou glacier)	Terrestrial ecosystems (forest)	Fungal community composition change during succession	Glacier retreat	H	pos	Tian et al. (2017)
Quinghai-Tibetan Plateau	Carbon sequestration and nitrogen cycle (tundra)	Change in Net Ecosystem Exchange causes loss of carbon and nitrogen accompanied by extremely slow vegetation recovery	Permafrost thaw	H	neg	Mu et al. (2017)
Himalayas (Ladakh)	Terrestrial ecosystems (tundra)	Decrease in dry-adapted plant cover	High snowfall and rapid freeze-thaw cycles	H	mixed	Dolezal et al. (2016)
Tibetan Plateau	Alpine cold meadow (tundra)	Decline in alpine cold meadow vegetation	Permafrost thaw increases thickness of active layer	H	neg	Wang et al. (2011)
Western Himalaya	Terrestrial ecosystems (tundra)	Herb species richness and abundance increases in treeline ecotone with earlier snowmelt	Earlier snow melt	M/H	pos	Adhikari (2018)
Northern China, Northwest China, Tibetan Plateau	Terrestrial ecosystems (forest)	Greater tree growth in regions with more snow; no effect of snow where snow accumulation is low	Snow accumulation	H	mixed	Wu et al. (2018)
Tibetan Plateau	Terrestrial ecosystems (tundra)	Greenness change for alpine meadow and alpine steppe across much of the Plateau	Permafrost presence or absence; soil moisture	M	mixed	Wang et al. (2016)
Greater Himalayan range and the Tibetan Plateau	Rangeland vegetation (tundra)	Changes in growing season (including shortening in dry areas), vegetation phenology, and lowered soil moisture	Shifted snow season	H	mixed	Paudel & Andersen (2013)
Himalayas	Northern Hemisphere vegetation cover including tundra	Increased growing-season productivity and soil moisture ("greening")	Changes in snow cover	H	pos	Wang et al. (2018)
Himalaya and Tibetan Plateau	Tourism	Changes in access routes to Baishui Glacier No. 1	Glacier retreat	M	neg	Wang et al. (2010)
Bhutan	Tourism	High elevation trekking: trails damaged and trekking routes limited	Increased runoff due to increased snowmelt and glacier melt	M	neg	Hoy et al. (2016)
Tibet	Culture	Spiritual value: a number of sacred mountains are altered, causing distress for the local population, who view this change as the product of their own spiritual and moral failings	Glacier retreat	M	neg	Salick et al. (2012)
Tibetan Plateau	Culture	Aesthetic value of glaciers reduced	Glacier surfaces have become dirtier	M	neg	Wang et al. (2017a)

Location	Affected sector or system	Impact	Cryosphere change	Attribution confidence	Positive/ negative/ mixed	Reference
Uttarakhand, India	Culture	Spiritual value – rising concern for local population who view the changes in sacred mountains as the product of their own religious and moral failings	Glacier retreat	M	neg	Drew (2012)
Nepal	Culture	Causing people to experience concern about divine beings and proper rituals	Reduced snow cover	M	neg	Becken et al. (2013)
Nepal	Migration	Increased emigration due to declining irrigation water and agricultural yields	Reduced runoff due to less snow cover	M	neg	Prasain (2018)
New Zealand, Japan, Other						
New Zealand	Landslides	Rock avalanches from lower permafrost limit	Thaw/degradation of permafrost	M	neg	Allen et al. (2011)
New Zealand	Freshwater ecosystems	Loss of cold tolerant taxa	Reduced runoff due to glacier decline	M	neg	Cadbury et al. (2010)
Japan (Taisetsu Mountains, Hokkaido)	Terrestrial ecosystems (tundra)	Changes in vegetation structure (shrubs & forbs)	Accelerated snow melt and drier soil conditions	M	mixed	Amagai et al. (2018)
Japan (Taisetsu Mountains, Hokkaido)	Terrestrial ecosystems (forest)	Plant (bamboo) encroachment into alpine zones	Changes in soil water dry-down rates associated with snowmelt	M	pos	Winkler et al. (2016)
New England, northeast USA	Tourism	Closure of ski resorts	Reduced snow fall and snow cover	H	neg	Beaudin and Huang (2014); Hamilton et al. (2003)

SM2.9 Details of Studies on Adaptations in Response to Cryosphere Changes

Table SM2.12 | Documented individual adaptation actions, per country (grouped by regions as defined in Figure 2.1), for sectors addressed in this chapter, i.e., Agriculture, Biodiversity, Water, Energy, Natural Hazards (Hazards), Tourism & recreation (Tourism), Settlements & habitability (Habitability), Intrinsic & cultural values (Cultural). 'Other' is a merged category for other sectors and 'Undefined' refers to adaptation where no clear classification to a specific sector could be allocated. The adaptations are listed across their scale of relevance and/or implementation (Local, Regional, Global), as well as classification of type of adaptation as either 'formal policy', 'autonomous' or 'undefined'. Key climatic drivers are listed that have links to (or changes in) cryosphere changes are described, which include: Temperature change 'Temperature'; Precipitation change in terms of amount and timing ('Precip. (amount, timing)'); Precipitation change in terms of changes in state (e.g., snow to rain) ('Precip. (phase)'); Glacier change where non-hydrological impacts were associated ('Glacier (non-hydro)'); Glacial hydrology change ('Glacier (hydro)'); Snow cover change where non-hydrological impacts were associated ('Snow (non-hydro)'); Snow hydrology change ('Snow (hydro)'); Extreme events where hydrological elements were associated ('Extremes (hydro)'); Extreme events that were not associated with a hydrological impacts ('Extremes (non-hydro)'); 'Permafrost thaw'; and ecosystem changes in terms of flora and/or fauna ('Ecosystem'). Entries for each region are sorted in alphabetical order of the references.

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
Alaska						
USA	Undefined	Multi-stakeholder adaptation planning exercise	Regional	Undefined	Snow (non-hydro), Ecosystem	Knapp et al. (2014)
Caucasus and Middle East						
Russia	Hazards	Instillation of GLOF (glacial lake outburst flood) early warning system	Regional	Formal Policy	Glacier (hydro), Extremes (hydro)	Petrakov et al. (2012)
Central Europe						
Switzerland	Water	Efforts of ACQWA projects to address vulnerability associated with hydrological changes	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro)	Beniston et al. (2011)
	Water, Hazards	Flooding/hazards planning – Third Rhone Correction	Local, Regional			
		Flooding/hazards planning – MINERVE				

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
Switzerland, Italy, Chile, Kyrgyzstan	Agriculture, Energy, Water	Impact assessment for adaptation planning	Global	Undefined	Temperature, Precip. (amount, timing, phase state), Glacier (hydro), Extremes (hydro, non-hydro), Permafrost thaw	Beniston and Stoffel (2014)
Spain	Tourism	Artificial snow production Nocturnal skiing Protection and conservation of snowpack Diversification of snow-based activities Expansion of skiable area Accessing economic assistance (government & insurance) Turning ski resorts into multi-recreation facility	Regional	Autonomous	Temperature, Precip. (amount, timing), Snow (non-hydro)	Campos Rodrigues et al. (2018)
France	Tourism, Hazards	Installation of ladders	Local	Autonomous	Temperature, Glacier (non-hydro, hydro), Permafrost thaw	Duvillard et al. (2015)
Austria	Tourism	Cover ski runs with textile to reduce ablation Grooming ski slopes	Local	Autonomous	Snow (non-hydro)	Fischer et al. (2011)
Switzerland Italy	Tourism	Cover snow with sawdust to preserve for skiing	Regional	Autonomous	Temperature, Precip. (amount, timing), Snow (non-hydro)	Grünewald et al. (2018)
Switzerland	Tourism	Installing a hanging bridge across the deep gorge to allow mountain access	Local	Autonomous	Glacier (hydro), Snow (hydro), Extremes (hydro), Permafrost thaw	Haeberli et al. (2016)
	Hazards	Installation of early warning system	Local	Undefined		
	Undefined	Project to support adaptation planning – NELAK	Regional	Formal Policy		
	Water	Lake level lowering Flood retention	Undefined	Undefined		
Switzerland	Water	Policy incentives for 'resilience-based' water infrastructure projects	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Hill (2013)
		Shared water utility service to spread risks among stakeholders Policy for reducing water use in periods of drought		Undefined		
Switzerland	Tourism	Artificial snow production Consortium for tourism planning and diversification	Undefined	Autonomous	Temperature, Glacier (non-hydro, hydro), Snow (non-hydro), Permafrost thaw, Ecosystem	Hill et al. (2010)
	Undefined	Project to support adaptation planning – CIPRA	Regional	Formal Policy		
Switzerland, France	Energy, Water	Glacier-fed rivers and climate change project – GLAC-HYDROECO-NET	Undefined	Formal Policy	Glacier (hydro), Ecosystem	Khamis et al. (2014)
France	Tourism	Establishment of Chamonix Department of Trail Maintenance	Local	Formal Policy	Temperature, Glacier (non-hydro, hydro), Permafrost thaw	Mourey and Ravanel (2017)
	Tourism, Hazards	Construction of bridge to access to refuge on Mont Blanc		Formal Policy		
		Route modifications, opening trail connecting other refuges Installation of ladders		Autonomous		

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
Austria, Germany, Switzerland	Undefined	Assessment of adaptation knowledge and needs	Global	Formal Policy	Glacier (hydro), Snow (hydro), Extremes (hydro)	Muccione et al. (2016)
Austria	Tourism	Switching to other tourism activities	Undefined	Undefined	Glacier (non-hydro), Snow (non-hydro)	Orlove (2009b)
Austria, Switzerland		Resorts covering glaciers				
Italy		Redistributing available snow				
Switzerland	Hazards	Creating hazard maps and restricting construction		Formal Policy	Glacier (hydro), Snow (non-hydro), Extremes (hydro)	
Spain	Tourism	Modelling how ski area change and tourism impacts in support of planning process	Undefined	Formal Policy	Temperature, Snow (non-hydro)	Pons-Pons et al. (2012)
Spain	Tourism	Artificial snow production	Undefined	Autonomous	Snow (non-hydro)	Pons et al. (2014)
	Undefined	Project to support adaptation planning – ESPON-CLIMATE		Formal Policy		
Austria	Tourism	Evaluation of impacts of climate change on alpine trails to support planning	Regional	Formal Policy	Glacier (hydro), Permafrost thaw	Ritter et al. (2012)
Austria	Tourism	Artificial snow production	Regional	Autonomous	Temperature, Snow (non-hydro)	Steiger and Mayer (2008)
High Mountain Asia						
India	Agriculture	Development of state action plan on climate change	Regional	Formal Policy	Precip. (amount, timing), Glacier (hydro), Extremes (hydro)	Azhoni and Goyal (2018)
		Hazard risk and vulnerability assessment to support planning				
	Agriculture, Water	Spring water rejuvenation project	Local			
India	Habitability	Building stone embankments to avoid flooding	Local	Undefined	Temperature, Precip. (amount, timing), Extremes (hydro)	Bhadwal et al. (2013)
	Other	Increase the range of crops covered under insurance				
	Undefined	Improving access to better technology in agriculture			Temperature, Precip. (amount, timing)	
	Agriculture	Capacity building for farmers for water efficient farm practice			Temperature, Precip. (amount, timing), Extremes (hydro)	
		Limiting cultivation of summerrice				
	Agriculture, Water	Field bunding to control erosion			Temperature, Precip. (amount, timing)	
		Afforestation				
	Water	Promoting water efficient irrigation				
		Construction of water harvesting and storage structure				
		Increase public awareness of water conservation			Temperature, Precip. (amount, timing), Extremes (hydro)	
		Knowledge sharing exercises				
		Water conservation structure like dams, surface water bodies, field bunding				
		Water harvesting structures				

2SM

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
Tajikistan	Agriculture, Energy, Culture, Habitability, Water, Other	Stakeholder workshop providing information for adaptation planning	Undefined	Formal Policy	Temperature, Precip. (amount, timing), Glacier (non-hydro)	Bizikova et al. (2015)
Nepal	Undefined	National Adaptation Programme of Action Nepal	Regional	Formal Policy	Snow (non-hydro), Extremes (hydro)	Byers et al. (2014)
		Local Adaptation Plan of Action				
		Research and monitoring of glacial lakes		Undefined		
		Early warning systems				
		Disaster management systems				
		Weather monitoring and forecasting				
		Snow and ice management training				
		Alternative house construction strategies				
		Public awareness building				
		Firefighting training and equipment				
	Other	Insurance coverage and clothing for porters	Regional	Undefined	Snow (non-hydro), Extremes (hydro)	
	Agriculture	Nurseries and afforestation				
Tajikistan	Undefined	Labour migration	Local	Autonomous	Glacier (hydro), Ecosystem	Christmann and Aw-Hassan (2015)
		Appointed villager to regularly check all glaciers				
		Opening a training centre for adaptation in mountain villages				
		Planting trees				
		Initiate a watershed development committee				
		Building water reservoir				
	Agriculture	Crop and livestock diversification				
		Supporting education of local person in agriculture and engineering to increase adaptation capacity in community				
Uzbekistan	Undefined	Participatory discussion of adaptation strategies for rangeland		Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro)	
	Agriculture	Establish pastoral user groups				
		Establish fenced seed isles for yearly natural seeding				
		Seasonal grazing management				
India	Water	Artificial glacier construction	Local	Autonomous	Temperature, Glacier (hydro)	Clouse (2014)
India	Water	Reservoirs built and snow fences installed to capture/ store snow in winter for use as irrigation in summer	Local	Autonomous	Snow (hydro)	Banerji and Basu (2010)

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
India	Undefined	Moving to new location to escape perennial water scarcity	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Clouse (2016)
		Reduce overall hectare of cropland in production				
		Shrink livestock holding to fit available pasturage				
	Habitability	Snow barrier bands				
	Habitability, Water	Building new irrigation canals and rerouting water		Formal Policy		
India	Culture	Use of reservoirs to store water	Regional	Autonomous	Temperature, Glacier (hydro)	Clouse et al. (2017)
	Water	Evaluation of artificial ice reservoirs				
	Agriculture	Installation of improved water mills				
	Agriculture, Water	Building ice stupa to store water	Local		Glacier (hydro), Snow (hydro)	
India	Agriculture	Government watershed improvement programs	Regional	Formal Policy	Glacier (hydro), Snow (hydro)	Dame and Nüsser (2011)
India	Undefined	Spread coal onto glaciers to ensure regeneration	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro)	Gagné (2016)
India, Nepal, Pakistan	Undefined	Collaborative adaptation research initiative – CARIAA	Regional	Formal Policy	Glacier (hydro), Snow (hydro)	Cochrane et al. (2017)
Nepal	Water	Multiple livelihood options to buffer against seasonal losses in one sector	Local	Autonomous	Precip. (amount, timing), Extremes (hydro, non-hydro)	Becken et al. (2013)
Nepal	Agriculture	Switching crop types	Local	Autonomous	Precip. (amount, timing), Glacier (hydro), Extremes (non-hydro)	Dewan (2015)
	Undefined	Early warning systems and community-based flood management				
		Training for flood preparedness and responses				
		Using traditional remedies to rehabilitate victims of diseases				
		Borrowing from neighbours				
		Vulnerable Group Feeding program		Formal Policy		
		Framework and strategy for disaster risk management				
		National strategy for disaster risk management				
		Flood risk reduction program				
	Water	Building tube wells for drinking water				
		Raising houses on stilts	Undefined	Undefined		
	Hazards	Funds to support social resilience				
China	Undefined	Policies to address the impact of permafrost degradation	Undefined	Formal Policy	Permafrost thaw	Fang et al. (2011)
		Special fund for climate change adaptation	Regional			
China	Undefined	Project to support adaptation planning – RECAST	Regional	Formal Policy	Precip. (amount, timing), Glacier (hydro)	Fricke et al. (2009)
China	Habitability	Relocation of settlement	Local	Autonomous	Extremes (hydro)	Diemberger et al. (2015)

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
China	Tourism	Assessment to support sustainable glacier tourism	Regional	Formal Policy	Temperature, Glacier (non-hydro)	Wang et al. (2010)
		Tourism diversification		Autonomous		
		Restricting tourism access		Formal Policy		
China	Agriculture	Shifting to different seasonal pasture	Local	Autonomous	Temperature, Precip. (amount, timing), Snow (non-hydro)	Fu et al. (2012)
		Sharing pasture within community				
		Cultivating fodder to feed in winter				
		Build small livestock sheds				
		Selling new products				
		Pasture management activities				
China	Agriculture, Water	Water saving irrigation measures	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro)	Gao et al. (2014)
	Agriculture	Rotational grazing		Undefined		
	Undefined	Fencing grassland and grass planting				
Nepal	Hazards	GLOF early warning system	Local	Formal Policy	Glacier (hydro), Extremes (hydro)	Kattelmann (2003)
Nepal	Agriculture	Creating community forest user groups			Temperature, Precip. (amount, timing), Extremes (hydro), Ecosystem	Gentle and Maraseni (2012)
		Reliance on traditional institutional arrangements		Autonomous		
		Storage of grains				
		Purchasing irrigated land				
		Switch to new agriculture technology/crop types				
		Institutional support from Community Forest User Groups				
	Agriculture, Culture, Water	Transhumant pastoralism as adaptation strategy				
	Undefined	Money lending				
		Cash saving				
		Take loans in times of food scarcity				
		Reduce food intake				
		Migration/selling labour				
Kyrgyzstan	Agriculture, Energy, Water	Impact assessment for adaptation planning	Global	Undefined	Temperature, Precip. (amount, timing, phase state), Glacier (hydro), Extremes (hydro, non-hydro), Permafrost thaw	Beniston and Stoffel (2014)
Kyrgyzstan	Agriculture	Introduction of new crops with lower water requirements	Local	Autonomous	Temperature, Glacier (hydro), Snow (hydro)	Hill et al. (2017)
Kyrgyzstan, Uzbekistan	Water	Establishment of centre for transboundary water governance	Regional	Formal Policy	Glacier (hydro)	Hoelzle et al. (2017)

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
India	Agriculture	Growing crops at higher altitudes	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro), Ecosystem	Ingty (2017)
		Regulate agriculture and grazing rights to allow ecosystem recovery				
		Storage and crop fodder				
	Agriculture, Culture	Reliance on traditional knowledge				
	Tourism	Diversify to tourism				
		Migration				
		State action plan on climate change	Regional	Formal Policy		
India	Habitability, Water	Evaluating efficacy of artificial glaciers	Local	Formal Policy	Glacier (hydro)	Nüsser et al. (2018)
India	Hazards	Disaster risk reduction demonstration in schools	Local	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Extremes (hydro)	Kaul and Thornton (2014)
	Agriculture	Populating potato and peas		Undefined		
	Agriculture, Other	Insurance schemes for crops	Undefined	Formal Policy		
India	Water	Participatory project to underpin adaptation planning	Local	Formal Policy	Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Kelkar et al. (2008)
	Agriculture	Plant less water-intensive crops				
		Irrigate fields timeshare				
	Undefined	Sell land and livestock				
		Find other jobs				
		Take loans				
Nepal	Agriculture	Crop diversification	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro), Extremes (hydro)	Konchar et al. (2015)
		Construction of greenhouses				
	Agriculture, Tourism	Diversify to tourism, agropastoralism, agroforestry				
	Undefined	New roofing material				
Nepal	Agriculture	Changing crops and agricultural practices using Indigenous and local knowledge	Local	Autonomous	Temperature, Snow (non-hydro), Snow (hydro)	Manandhar et al. (2011)
Nepal	Tourism	Assessment of ecotourism as adaptation measure for conservation area	Regional	Undefined	Precip. (amount, timing, phase state), Extremes (non-hydro)	Adler et al. (2013)
Nepal	Habitability	Local relocation of settlement after decreased water supply	Local	Autonomous	Snow (hydro)	Barnett et al. (2005)
Nepal	Agriculture	Crop diversification	Local	Autonomous	Temperature, Precip. (amount, timing), Snow (non-hydro)	Onta and Resurreccion (2011)
	Undefined	Cross border trade and day labour trips				
Nepal	Water	Lake lowering	Regional	Formal Policy	Extremes (hydro)	Orlove (2009b)
Nepal	Undefined	Project to support adaptation planning – Climate Witness Project	Regional	Formal Policy	Glacier (hydro), Snow (non-hydro), Extremes (hydro)	Rai and Gurung (2005)
		Establishing a Designated National Authority				

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
Nepal	Undefined	Lake lowering	Undefined	Formal Policy	Glacier (hydro), Extremes (hydro)	Somos-Valenzuela et al. (2015)
		Modelling impact of GLOF to support planning				
Nepal	Water	Limiting water consumption to drinking and cooking requirements	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Extremes (hydro)	McDowell et al. (2013)
		Roof water collection system				
		Hire assistants to help with water retrieval activities				
	Undefined	Collecting fuelwood for heating				
Nepal, India	Hazards, Water	Bilateral Committee on Flood Forecasting	Regional	Formal Policy	Glacier (hydro), Snow (hydro), Extremes (hydro)	Lebel et al. (2010)
India	Agriculture	Crop diversification	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Meena et al. (2019)
		Change timing of agricultural activities				
		Agropastoralism to diversify livelihood				
India	Agriculture	Changing agricultural patterns	Local	Autonomous	Precip. (amount, timing), Glacier (hydro), Extremes (hydro)	Maikhuri et al. (2017)
		Switching to other types of animal husbandry				
		Adopt horticulture				
		Establish forest councils and village forest committee				
		Migration				
	Undefined	Take loans and insurance				
Bhutan	Hazards	Instillation of GLOF early warning system	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro), Extremes (hydro)	Meenawat and Sovacool (2011)
	Undefined	Lowering lake water levels				
		Community awareness and capacity building activities				
		GLOF Risk Reduction Projects				
Bhutan, Nepal	Undefined	Assessment of adaptation knowledge and needs	Global	Formal Policy	Glacier (hydro), Snow (hydro), Extremes (hydro)	Muccione et al. (2016)
India	Water	India National Action Plan on Climate Change	Undefined	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Extremes (hydro)	Moors et al. (2011)
		National Water Policy				
		Project to support adaptation planning – Highnoon	Regional			
India	Agriculture	Crop diversification	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Ecosystem	Negi et al. (2017)
		Crop diversification				
		Agropastoralism to diversify livelihood				
		Convert irrigated land into rainfed				
		Switching away from livestock rearing				
		Use of moisture conserving cropping techniques				
	Undefined	Migration			Extremes (hydro)	

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
Pakistan	Habitability	Relocation after hazard event	Local	Autonomous	Extremes (hydro, non-hydro)	Kreutzmann (2012)
Pakistan	Water	Construction of water channels for irrigation and domestic water supply	Local	Autonomous	Glacier (hydro)	Nüsser and Schmidt (2017)
Pakistan	Undefined	Migration	Local	Autonomous	Glacier (hydro), Snow (hydro)	Parveen et al. (2015)
Pakistan	Undefined	Household renovations	Local	Autonomous	Precip. (amount, timing), Glacier (hydro), Extremes (hydro, non-hydro)	Shah et al. (2017)
		Precautionary savings				
Pakistan	Water	Irrigation scheme/program	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro)	Spies (2016)
		Poverty alleviation and physical infrastructure development program				
Kyrgyzstan, Tajikistan, Uzbekistan, Kazakhstan	Undefined	Identification of steps for overcoming adaptation challenges – ACQWA project	Regional	Formal Policy	Temperature, Glacier (hydro), Snow (hydro)	Sorg et al. (2014b)
Kyrgyzstan, Tajikistan	Water	Water user associations	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Stucker et al. (2012)
		Water allocation strategy				
		Water rationing				
		Water sharing				
		Integrate Integrated Water Resource Management (IWRM) principles into institutions	Local	Undefined		
		Clean and repair canals		Autonomous		
	Agriculture	Expand orchards				
		Do not plant a second crop				
		Crop diversification				
	Hazards	Early warning system		Formal Policy		
	Undefined	IWRM project	Undefined			
Kazakhstan	Agriculture, Biodiversity, Energy, Hazards, Water	Development of sectoral adaptation plans	Regional	Formal Policy	Glacier (hydro), Snow (hydro), Extremes (hydro)	Xenarios et al. (2018)
	Agriculture, Habitability, Water	Introduction of water saving technologies				
	Agriculture	Decrease livestock pressure on pasture				
		Realization of pasture management plans				
		Establishment of the Public Seed Funds				
Tajikistan	Water	Development of water user associations	Local			
	Agriculture, Biodiversity, Water	Environmental land management and rural livelihoods project				

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
Tajikistan	Agriculture, Hazards, Water	Capacity strengthening and livelihood diversification project	Local	Formal Policy	Glacier (hydro), Snow (hydro), Extremes (hydro)	Xenarios et al. (2018)
Tajikistan	Habitability	Infrastructure improvements	Local	Autonomous	Glacier (hydro), Snow (hydro), Extremes (hydro)	Xenarios et al. (2018)
Tajikistan	Hazards	Developing evacuation maps	Local	Autonomous	Glacier (hydro), Snow (hydro), Extremes (hydro)	Xenarios et al. (2018)
Tajikistan	Hazards	Constructing shelters for hazard protection	Local	Autonomous	Glacier (hydro), Snow (hydro), Extremes (hydro)	Xenarios et al. (2018)
Tajikistan	Hazards	Training of volunteers for the search and rescue activities	Local	Autonomous	Glacier (hydro), Snow (hydro), Extremes (hydro)	Xenarios et al. (2018)
Kazakhstan, Kyrgyzstan, Tajikistan	Agriculture, Biodiversity, Water	Initiation of Ecosystem-based Adaptation (EbA)	Regional	Formal Policy	Glacier (hydro), Snow (hydro), Extremes (hydro)	Xenarios et al. (2018)
Kazakhstan, Kyrgyzstan, Tajikistan	Agriculture, Hazards, Water	Knowledge sharing arrangements	Regional	Formal Policy	Glacier (hydro), Snow (hydro), Extremes (hydro)	Xenarios et al. (2018)
Kazakhstan, Kyrgyzstan, Tajikistan	Agriculture, Water	Documentation, dissemination, and preservation of local knowledge relevant to adaptation	Local	Formal Policy	Glacier (hydro), Snow (hydro), Extremes (hydro)	Xenarios et al. (2018)
Low Latitudes (Andes)						
Bolivia	Undefined	Migration	Local	Autonomous	Glacier (hydro)	Brandt et al. (2016)
Bolivia	Water	Construction of reservoirs for water storage	Regional	Formal Policy	Temperature, Precip (amount, timing), Glacier (hydro)	Buytaert et al. (2017)
Bolivia	Undefined	Migration	Local	Autonomous	Temperature, Glacier (hydro), Snow (hydro), Extremes (hydro)	Kaenzig (2015)
Bolivia	Tourism	Rebranding the loss of glaciers as an opportunity for 'last chance tourism'	Regional	Autonomous	Temperature, Precip. (amount, timing), Snow (hydro)	Kaenzig et al. (2016)
Bolivia	Agriculture	Switching to cash crops	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro), Extremes (hydro), Permafrost thaw, Ecosystem	McDowell and Hess (2012)
Bolivia	Agriculture	Night irrigation	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro), Extremes (hydro), Permafrost thaw, Ecosystem	McDowell and Hess (2012)
Bolivia	Agriculture	Delay planting until irrigation is available	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro), Extremes (hydro), Permafrost thaw, Ecosystem	McDowell and Hess (2012)
Bolivia	Undefined	Migrating to nearby towns to work	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro), Extremes (hydro), Permafrost thaw, Ecosystem	McDowell and Hess (2012)
Bolivia	Undefined	Sharing work between community members	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro), Extremes (hydro), Permafrost thaw, Ecosystem	McDowell and Hess (2012)
Bolivia	Undefined	Participatory vulnerability assessment to inform adaptation	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro), Extremes (hydro), Permafrost thaw, Ecosystem	McDowell and Hess (2012)
Bolivia	Undefined	Migration	Local	Autonomous	Glacier (hydro)	Yager (2015)
Bolivia	Water	Project to support adaptation planning – PPCR	Undefined	Formal Policy	Temperature, Ecosystem	Huggel et al. (2015)
Bolivia, Colombia, Ecuador, Peru	Agriculture, Biodiversity, Water	Project to support adaptation planning – PRAA	Undefined	Formal Policy	Temperature, Ecosystem	Huggel et al. (2015)
Colombia	Agriculture, Habitability, Water	Project to support adaptation planning – INAP	Undefined	Formal Policy	Temperature, Ecosystem	Huggel et al. (2015)
Colombia	Biodiversity, Water	Project to support adaptation planning – Macizo Colombiano	Undefined	Formal Policy	Temperature, Ecosystem	Huggel et al. (2015)
Peru	Agriculture, Hazards, Water	Project to support adaptation planning – Proyecto Glaciares; PACC	Undefined	Formal Policy	Temperature, Ecosystem	Huggel et al. (2015)
Peru	Hazards, Water	Project to support adaptation planning – IMACC	Undefined	Formal Policy	Temperature, Extremes (hydro)	Huggel et al. (2015)

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
Ecuador	Agriculture, Hazards, Other	Climate Change Action Plan	Undefined	Formal Policy	Temperature, Precip (amount, timing), Extremes (hydro)	Anguelovski et al. (2014)
Ecuador	Water	Construction of infrastructure to transfer water between basins	Regional	Formal Policy	Temperature, Precip (amount, timing), Glacier (hydro)	Buytaert and De Bièvre (2012)
Peru, Chile	Water	Establishment of adaptation plan	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Mills-Novoa et al. (2017)
Colombia, Peru	Undefined	Assessment of adaptation knowledge and needs	Global	Formal Policy	Glacier (hydro), Snow (hydro), Extremes (hydro)	Muccione et al. (2016)
Peru	Undefined	Migration	Local	Autonomous	Glacier (hydro)	Alata et al. (2018)
Peru	Water	National Water Authority	Local	Formal Policy	Temperature, Glacier (hydro)	Bury et al. (2013)
Peru	Undefined	GLOF assessment	Regional	Formal Policy	Temperature, Extremes (hydro)	Carey et al. (2012)
	Habitability, Water	GLOF prevention program through monitoring and engineering projects				
	Water	Initiation of GLOF assessment program				
		Installation of floodgates to control water level			Glacier (hydro), Extremes (hydro)	
		National System of Hydrological Resource Management				
Peru	Water	Project to support adaptation planning – CGIAR	Regional	Formal Policy	Glacier (hydro)	Condom et al. (2012)
Peru	Agriculture, Biodiversity, Culture, Tourism, Water		Local	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro)	Doughty (2016)
Peru	Agriculture	Crop diversification	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro)	Doughty (2016)
Peru	Water, Hazards	Potential for multi-purpose projects to address GLOFs and water availability	Regional	Undefined	Glacier (hydro), Extremes (hydro)	Drenkhan et al. (2019)
Peru	Undefined	Project to support adaptation planning – CONAM + IGP	Regional	Formal Policy	Glacier (hydro)	Lagos (2007)
Peru	Undefined	Project to support adaptation planning – Adapts project	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Lasage et al. (2015)
	Agriculture, Biodiversity	Protection of upstream forests				
	Water	Surface storage dams				
	Agriculture	Low-cost gravity drip irrigation system	Local			
		Changing the frequency of irrigation				
		Crop diversification				
	Water	Water harvesting using roof-water systems				

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
Peru	Undefined	Establish an integrated regional database on natural resources, climate, and vulnerability	Regional	Undefined	Temperature, Precip. (amount, timing), Glacier (hydro), Extremes (hydro)	Lee et al. (2014)
		Align the national and regional institutional and legal frameworks to deal with the expected effects of climate change				
		Integrated management of reforestation, soil conservation, terrace management, monitoring systems, and capacity building				
		National Climate Change Strategy				
	Water	Construction of small structures for water storage and distribution and improved management of irrigated areas				
	Hazards	Integrating existing early warning systems to enhance emergency management				
	Agriculture	Conserving native crop varieties				
		Pest management practices				
		Improved pastures and fodder conservation practices				
Peru	Agriculture	Reducing planting activities	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro)	Lennox and Gowdy (2014)
Peru	Agriculture	Crop diversification	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Extremes (hydro)	Lennox (2015)
		Moving to livestock-based economy to sell milk rather than planting crops			Precip. (phase state)	
Peru	Agriculture	Livestock, land, and labour diversification	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Extremes (hydro), Permafrost thaw	Lopez-i-Gelats et al. (2015)
		Economic diversification				
Peru	Agriculture, Energy	Project to support adaptation planning – PROCLIM	Regional	Formal Policy	Precip. (amount, timing), Extremes (hydro)	Orlove (2009a)
Peru	Agriculture	Line irrigation canals with cement and install plastic pipes	Local	Autonomous	Glacier (hydro), Snow (hydro)	Orlove et al. (2019)
Peru	Undefined	Glacier change assessment in support of adaptation planning	Undefined	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro)	Peduzzi et al. (2010)
Peru	Agriculture	Changing agricultural calendar	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (non-hydro), Extremes (hydro), Ecosystem	Postigo (2014)
		Increasing pesticide use				
		Crop diversification				
		Cultivating in furrows				
		Burning shrubs, grass, manure to generate heat				
		Increasing livestock mobility				
	Water	Water boards regulating water				
Peru	Agriculture	Pasture rotation	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro), Ecosystem	Postigo et al. (2008)
		Creating irrigation channel		Formal Policy		
Peru	Water	Hillside infiltration systems in grasslands	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro)	Somers et al. (2018)

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
Peru	Water	Election of water allocator	Local	Autonomous	Glacier (hydro), Extremes (hydro)	Stensrud (2016)
		Making micro dams	Undefined	Formal Policy		
		Installing water pipes	Regional			
Peru	Water	Migration to towns for work	Local	Autonomous	Glacier (hydro), Extremes (hydro)	Wrathall et al. (2014)
Peru	Agriculture	Livelihood diversification	Local	Autonomous	Precip. (amount, timing), Glacier (hydro), Extremes (hydro)	Young and Lipton (2006)
		Getting grazing rights to other areas				
		Agricultural and crop diversification				
	Water	Timed allocation of water flow to individuals				
	Undefined	Seeking foreign funding, skills, attention for help				
	Other	Migration				
	Biodiversity	Conservation corridor		Formal Policy		
New Zealand						
New Zealand	Tourism	Constructing cantilevered bridge to the glacier	Regional	Autonomous	Temperature, Precip. (amount, timing), Glacier (non-hydro)	Espiner and Becken (2014)
		Using boats to ferry tourists after glacial lake appeared				
New Zealand	Tourism	Artificial snow production	Regional	Autonomous	Snow (non-hydro)	Hopkins and Maclean (2014)
		Transitioning to year-round tourism				
		Forming conglomerate business ventures				
		Developing new ski slopes				
New Zealand	Tourism	Assessment of stakeholder perceptions for adaptation planning	Regional	Formal Policy	Glacier (non-hydro), Snow (non-hydro)	Stewart et al. (2016)
Scandinavia						
Norway	Tourism	Changing activities at ski area	Regional	Autonomous	Temperature, Precip. (amount, timing), Snow (non-hydro)	Demiroglu et al. (2018)
		Changing time of use of ski area				
		Changing ski areas within Norway				
		Artificial snow production				
		Salting glacier surface				
Norway	Tourism	Diversifying locations of tourism activity	Undefined	Autonomous	Glacier (non-hydro)	Furunes and Mykletun (2012)
Norway	Energy	Water resource and energy directorate	Undefined	Formal Policy	Glacier (hydro)	Orlove (2009a)
Southern Andes						
Chile	Undefined	Participatory project to identify adaptive options	Regional	Formal Policy	Precip. (amount, timing), Snow (hydro)	Aldunce et al. (2016)
Chile	Habitability	Local relocation of settlements after GLOF event in 1977	Local	Formal Policy	Extremes (hydro)	Anacona et al. (2015b)

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
Chile	Agriculture, Energy, Water	Impact assessment for adaptation planning	Global	Undefined	Temperature, Precip. (amount, timing, phase state), Glacier (hydro), Extremes (hydro, non-hydro), Permafrost thaw	Beniston and Stoffel (2014)
Chile	Agriculture	Provide financing and subsidies to farmers	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (non-hydro), Snow (hydro)	Clarvis et al. (2014)
Chile	Water	Declaration of drought zones	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (non-hydro), Snow (hydro)	Clarvis et al. (2014)
Chile	Water	Water data system improvement	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (non-hydro), Snow (hydro)	Clarvis et al. (2014)
Chile	Water	Water transfer using trucks	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (non-hydro), Snow (hydro)	Clarvis et al. (2014)
Chile	Water	Dam construction	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (non-hydro), Snow (hydro)	Clarvis et al. (2014)
Chile	Water	Traditional water distribution strategies	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (non-hydro), Snow (hydro)	Clarvis et al. (2014)
Chile	Water	Crop diversification	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (non-hydro), Snow (hydro)	Clarvis et al. (2014)
Chile	Water	Water allocation policy	Regional	Formal Policy	Temperature, Glacier (hydro), Snow (hydro)	Hill (2013)
Chile	Water	Infrastructure to support irrigation security	Regional	Formal Policy	Temperature, Glacier (hydro), Snow (hydro)	Hill (2013)
Chile	Water	Policies for drought periods	Regional	Formal Policy	Temperature, Glacier (hydro), Snow (hydro)	Hill (2013)
Chile	Water	Policy to improve irrigation efficiency	Regional	Formal Policy	Temperature, Glacier (hydro), Snow (hydro)	Hill (2013)
Chile	Water	Policy for better water resources management under increasing scarcity	Regional	Formal Policy	Temperature, Glacier (hydro), Snow (hydro)	Hill (2013)
Chile	Water	Water allocation policy	Regional	Autonomous	Temperature, Glacier (hydro), Snow (hydro)	Hill (2013)
Chile	Undefined	Reinforcing doors and roofs	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Young et al. (2010)
Chile	Undefined	Couples do not marry to receive subsidy to increase portable water	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Young et al. (2010)
Chile	Agriculture	Migration to areas with more vegetation	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Young et al. (2010)
Chile	Agriculture	Companies using more efficient irrigation systems	Undefined	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Young et al. (2010)
Chile	Agriculture	Public funds made available to improve irrigation efficiency	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Young et al. (2010)
Chile	Water	Companies securing water rights	Undefined	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Young et al. (2010)
Chile	Water	Creating water storage ponds	Local	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Young et al. (2010)
Chile	Water	Subsidies made available for single mother for water payments	Local	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Young et al. (2010)
Chile	Water	Reducing intake of water canals	Regional	Autonomous	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Young et al. (2010)
Chile	Water	Reduce water use and seize water rights	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Young et al. (2010)
Chile	Water	Policy to extend water access	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Young et al. (2010)
Chile	Water	Constructing water canals and pool structures	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Young et al. (2010)
Chile	Hazards	Municipal Emergency Committee provides alerts for harsh seasons	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Young et al. (2010)
Peru, Chile	Water	Adaptation plan for water management	Regional	Formal Policy	Temperature, Precip. (amount, timing), Glacier (hydro), Snow (hydro)	Mills-Novoa et al. (2017)

Region country	Sector	Description of adaptation	Scale of relevance/ implementation	Type of adaptation	Climatic driver of adaptation	Reference
Argentina, Chile, Bolivia	Undefined	Baseline assessment to support adaptation – SSHRC	Regional	Formal Policy	Temperature, Glacier (hydro), Snow (hydro), Extremes (hydro)	Montana et al. (2016)
		Baseline assessment to support adaptation – IAI				
		Baseline assessment to support adaptation – CLACSO-CROP				
Argentina	Habitability, Water, Other	Glacier protection law Argentina	Regional	Formal Policy	Glacier (non-hydro, hydro)	Anacona et al. (2018)
Chile		Glacier protection law Chile				
Western Canada and USA						
Canada	Tourism	Artificial snow production	Local	Undefined	Snow (hydro)	Da Silva et al. (2019)
Canada	Hazards, Habitability	Creation of adaptation strategy	Local	Formal Policy	Temperature, Precip. (amount, timing), Extremes (hydro), Ecosystem	Picketts (2013)
Canada	Hazards, Habitability	Creation of steering committee for adaptation planning	Local	Formal Policy	Temperature, Precip. (amount, timing), Extremes (hydro)	Picketts et al. (2016)
Canada	Tourism	Artificial snow production	Undefined	Undefined	Glacier (non-hydro), Snow (non-hydro)	Orlove (2009a)
USA		Creation of the Sustainable Slopes program				
USA	Undefined	Establishment of adaptation partnerships	Global	Formal Policy	Temperature, Precip. (amount, timing), Snow (hydro)	Halofsky et al. (2018)
USA	Tourism	Artificial snow production	Local	Undefined	Snow (hydro)	Hagenstad et al. (2018)
		Diversification of tourism to other seasons/non-snow reliant		Autonomous		
USA	Undefined	Infrastructure to support fish and ranchers	Regional	Formal Policy	Temperature, Glacier (hydro), Snow (hydro)	McNeeley (2017)
		Establishment of Tribal Climate Resilience Program	Local			
		Establishment of Climate Science Centers and Landscape Conservation Cooperative				
USA	Undefined	Assessment of adaptation knowledge and needs	Global	Formal Policy	Glacier (hydro), Snow (hydro), Extremes (hydro)	Muccione et al. (2016)
USA	Tourism	Develop alternative tourism (local heritage, wildlife viewing)	Local	Autonomous	Glacier (non-hydro), Snow (non-hydro)	Orlove et al. (2019)
USA	Habitability	Vulnerability analysis and adaptations strategy	Local	Formal Policy	Temperature, Precip. (amount, timing), Snow (hydro), Extremes (hydro)	Strauch et al. (2015)
Iceland						
Iceland	Tourism, Hazards	Participatory planning to shift to safer glacier hiking routes	Local	Autonomous	Glacier (non-hydro)	Welling et al. (2019)

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