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Impact of climate change on the snow-covered area over the transboundary Jhelum River basin of the Himalayas region using Remote Sensing

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Abstract. Climate change is one of the pertinent issues for the 21st century mainly for the transboundary river basins because it has parallel impacts on the hydrosphere and cryosphere. The temperature changes impacted the snow-covered area (SCA) of the river basins. MODIS MOD10A2 product data was used to delineate the SCA for the Jhelum River basin. The catchment is further divided into elevation zones using DEM to delineate the SCA for every zone. The temperature changes were plotted against the SCA, and correlation analysis was used to see the impact of climate change on the SCA. The seasonal trend of SCA has depicted an increase in SCA during the spring and summer seasons and decreasing trend during autumn while winter shows stability. The snow cover depletion curve (SCDC) showed that snow is maximum in December, January, and February while its minimum during July and August. The correlation analysis of temperature and SCA for the period of 2001-2017 illustrated the inverse relationship, which depicted that a slight increase in temperature may trigger the fastest depletion in the snow-covered areas generating water issues for snow/glacier-fed river basins.

Keywords: Snow-covered, Transboundary, MODIS, SCA, SCDC, Jhelum River Basin.

1. Introduction

Climate change is one of the leading environmental issues due to greenhouse gases (GHG) in the 21st century, and it has global impacts on the hydrological cycle as well as the hydrology of a region (Stocker, 2013). Climate change is one of the burning topics attracting everyone's devotion over the last few decades. This climatic changes for longer periods either due to human activity or as a result of natural variability referred to as climate change. Climate change is mentioned as a change in climate that is due to indirectly or directly dependent on anthropogenic activities that have changed the global Atmosphere composition (Solomon et al., 2007). Climate change defines as any change for an extended period in the climate of a city or region or the Earth's climate from a broader perspective. These changes include cooling, warming, and temperature changes (Alexander et al., 2011).

The Fifth Assessment Report of the IPCC (IPCC, 2014) describes that global mean surface temperature including both ocean and land calculated from 1880 to 2012 considering linear trend, shows warming of 0.85°C (0.65–1.06)°C in comparison with a disturbing rise of 0.78 (0.72–0.85)°C that been recorded from 2003 to 2012 (Stocker, 2013). The Earth's temperature is rising continuously, and its impacts are significant on our freshwater supplies which ultimately affect agriculture. As the rise in temperature triggers the snow and glacial melting as well as enhances the rate of evapotranspiration which leads to cloud formation (Bolch et al., 2019; Sabin et al., 2020). The temperature changes greatly impact the whole dynamics of the hydrosphere of any region by disturbing the snow/glacier dynamics (Moazzam et al., 2022a; Moazzam et al., 2022b). Climate change is a long-term variation in the state of climatic indicators that continues for a longer period, typically from decades to millions of years.

Earth's climate is dynamic and faced continuous transformations in its weather patterns since its origin. The Earth is facing an interglaciation age and the temperature of the Earth system is rising naturally. Glaciation and interglaciation are interchangeable periods over the Earth that is due to the natural variability in the climate of the Earth's surface. In recent times the interglaciation age is accelerated due to climate change. Climate change term has become very famous instead of natural climatic variability because this rise in temperature phenomenon is enhanced due to anthropogenic activities. These anthropogenic activities influenced the Earth's climate since the industrial era. The rate of rising temperature in the last few decades has increased rapidly (Dawood et al., 2018; Rafiq et al., 2022), and this high temperature is causing glaciers to melt fast and retreat. The fastest melting of the glaciers has threatened the natural systems and caused problems in the runoff as well as flooding in low-lying areas (Rahman et al., 2017). Glacier and snow melting have affected the stream flow and caused floods in the recent decade especially affecting Pakistan on a large scale (Rahman et al., 2017; Saddique et al., 2019). The repeatedly flooding phenomenon in Pakistan reveals that uncertainty in runoff due to glacier melting causes variation in temperature and precipitation patterns (Dawood et al., 2017; Munawar et al., 2021). Climatic change also influences the precipitation and temperature patterns, especially temperature is the single most important indicator of changing climate (Dawood et al., 2018; Rafiq et al., 2022).

The snow melting process in any watershed involves energy that energy interacts with the mountainous tops and glaciers directly from solar radiation. Snow has maximum reflection and returns these shortwave radiations without absorption (Butt, 2012). This process of bouncing back solar radiation into the atmosphere is known as albedo. In this, the energy amount interacts with snow cover in terms of short-wave radiation and can't trigger the process of snow melting. The longwave radiation in terms of infrared also interacts with these snow cover tops from many sources such as water vapors of the atmosphere, carbon dioxide, and ozone provides energy for snow melting (van Vuuren et al., 2011). This energy is used by snowpacks to generate snow melting processes and feed rivers. Ground heat is also a factor other than radiation that help in snow melting.

The glaciated tops and snow-covered mountains of the Jhelum basin strongly specify about the future runoff and the water flow generated in the upcoming century. Glaciers are the most abundant freshwater source in the hydrosphere (Tahir et al., 2011). The glaciers of the Himalayas are one of the huge concentrations of ice exterior to the Polar Regions and feed major river systems of South Asia. Remote sensing techniques allow spatial and temporal variability of the large and inaccessible snow-covered areas, which are the basic components of the water cycle (Immerzeel et al., 2009). The hydrology of river basins is affected by regional warming because glacial melting accelerated for the simulation period. Snow cover area delineation using MODIS product and generating snow cover depletion cover proved a more useful and efficient method as compared to the ground observation data (Homan et al., 2011). The transboundary mountainous river Jhelum flows through India and Pakistan, the river basin has the least number of permanent glaciers, and river flow is primarily dependent on seasonal snow melting and snow cover area (Sharma et al., 2012). For the water resource management of the basin, accurate measurements of snow cover and snow melting are crucial because they take part in the river runoff. The MODIS 8-day snow cover products have been used and proved effective to study snow-covered areas to analyze the SCA changes (Snehmani et al., 2016).

2. Material and Methods

2.1. Study Area

The study area is part of the upper Indus basin and is located in northern Pakistan. The selected river basin is the transboundary river between India and Pakistan. The river basin is the catchment of the second-largest tributary of the Indus River. The geographical extent of the basin lies between 73-75.63°E and 33-35.1°N occupying a total area of about 34,475 km^2 (Fig. 1).

The catchment is mainly covered with the snow/glacial tops and Jhelum River is fed primarily by the melting of the glacier/snow melting those drains. The Jhelum River basin also covered the almighty Western Himalaya mountains with a height variation of 235-6200 meters. The basin has a diverse topography and a variety of geomorphology that has impacted its climatic and hydrological processes (Rather et al., 2017). The climatic conditions of the basins also have diversity due to the great Spatio-temporal variability of the basin. The basin precipitation is dominated by two precipitation patterns, summer is dominated by the monsoon precipitation while winter is covered by the western disturbances. The northern part of the basin is colder as compared to the southern region due to relief variations.

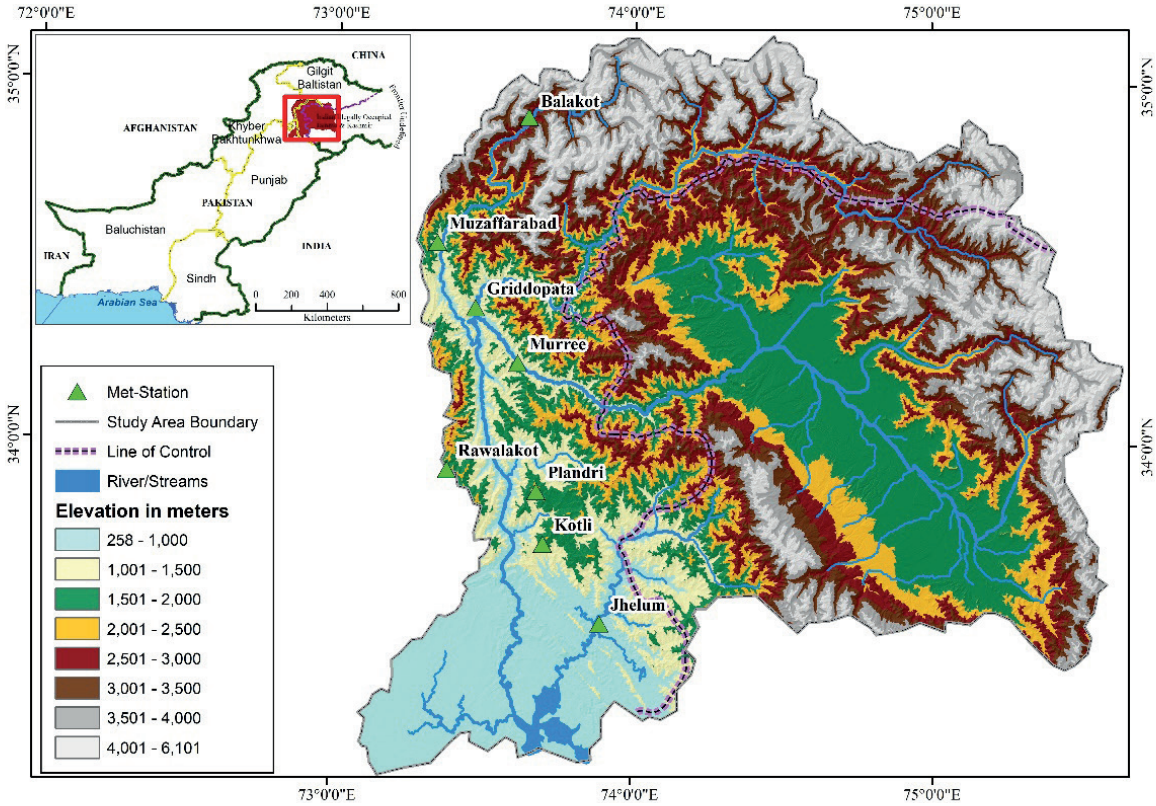

Figure 1. The geographical location of Pakistan and the Jhelum River basin

2.2. Data Description

The observed data of temperature was acquired from the Pakistan Meteorological Department (PMD) from 2001-2018. The missing values were replaced using an interpolation technique for some stations (Ali et al., 2019).

For topographical details of the study area, the Global Digital Elevation Model (GDEM) from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) of 30 m resolution was used to delineate the watershed and streams of the transboundary river Jhelum basin. The tiles covering the study area were mosaicked and further analysis performed using the hydrological toolbar of ArcGIS. The catchment area till the Mangla Dam extracted from the GDEM and the weather stations present in the study area were identified. The study has elevation ranges between 250-6100 m that have been further classified into seven zones based on height to analyze the snow cover depletion in every zone.

The MODIS product MOD10A2 was downloaded for the period of 2001-2018 period from the National Snow and Ice Data Center (NSIDC) site ("https://nsidc.org/data/modis/,"). The spatial resolution of MOD10A2 snow cover product is 500m*500m.

3. Methodology

3.1. Zones Classification

The GDEM was classified into seven different zones to study the response of SCA at a different elevations. The zone classification was based on the following Table 1.

Table 1. Area for each elevation zone

Zone	Elevation class (masl)	Mean elevation (masl)	Area (km^2)	Area (%)
I (A)	250-1000	615	6240	17
II (B)	1000-2000	1550	1393	5
III (C)	2000-2500	2150	5914	16
IV (D)	2500-3000	2850	5598	17
V (E)	3000-3500	3350	4956	13
VI (F)	3500-4000	3650	5382	17
VII (G)	4000-6063	5132	5046	15

SCA for every zone was delineated and plotted to view the fastest effect of climatic changes in each elevation zone. The basin had great variation in height from north to south that impact the climatic conditions. The variety in relief and climatic conditions has impacts on the glaciation and deglaciation of the zones.

3.2. MODIS snow cover

The MODIS 8-day product (MOD10A2) provided the snow-covered area through Spatio-temporal details of the Jhelum River basin. Snow cover products were obtained from the MODIS spectral band 4 (0.545μm-0.565μm) and band 6 (1.628μm-1.652μm). These bands were further used to analyze the snow-covered area by Normalized Difference Snow Index (NDSI) by applying the following equation:

$$NDSI = \frac{\text{band4} - \text{band6}}{\text{band4} + \text{band6}}$$

In the bare land a pixel with NDSI value of less or equal to 0.4 is considered snow and the alternative algorithm is used for the Normalized Difference Vegetation Index (NDVI) for the forest region (Immerzeel et al., 2009). NDSI is effectively applied to delineate snow-covered areas using multiple sensors (Dankers & De Jong, 2004). The snow-covered area was calculated for different hypsometric zones to study the snow dynamics regarding height for the period of 2001-2018.

3.3. Snow cover depletion curve (SCDC)

Snow-covered area for each month was calculated for every year and the snow-covered area was drawn to view the changes in the basin. The snow-covered area depletion curve highlight the fastest depletion year for snow. This also defines the snow accumulation and snow depletion per annum and month for the basin.

3.4. Snow-covered area vs temperature

Snow-covered area plotted against the temperature and correlation coefficient drawn to view the relationship between both parameters. The temperature being the climatic factor plays a dominant role in increasing or decreasing the snow-covered area. The snow accumulation and melting further impact the hydrological dynamic of the zone.

4. Results

The Jhelum River basin is divided into seven zones (Fig. 2) to analyze the snow depletion in each zone as height variation in the basin has its impacts on the snow cover area.

The cumulative depletion curve (CDC) was used to construct snow depletion curves (SDC) for the Jhelum River basin for the period of 2001-2017 in different hypsometric zones (Fig. 3). The snow depletion starts from March from

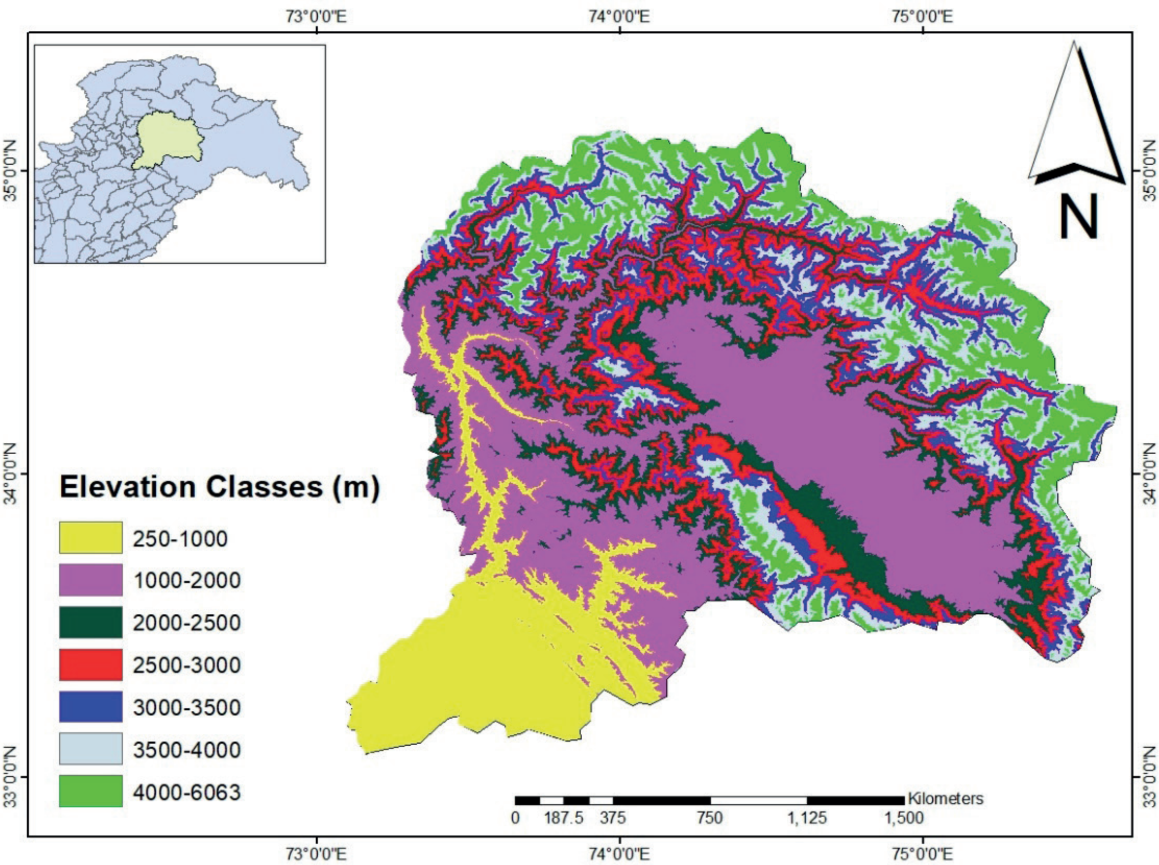

Figure 2. Zone classification based on height

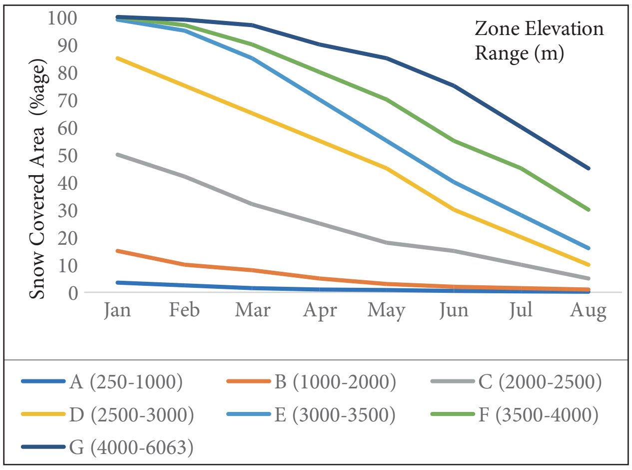

Figure 3. Snow-covered areas for different elevation zones

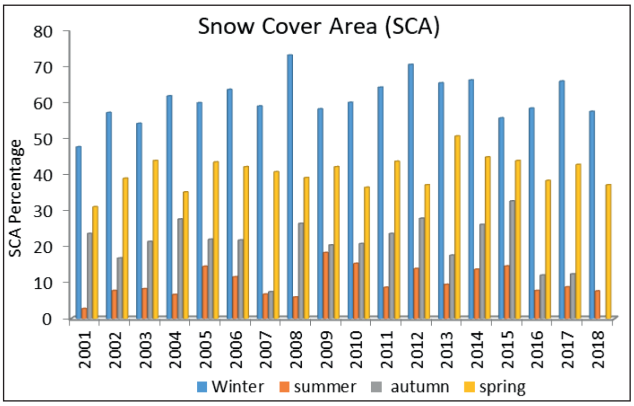

Figure 4. Seasonal variation in Snow Cover Areas – 2001 to 2018

low elevation zones and moves to higher elevation zones and the analysis of SDC showed that snow in Zone A and Zone B almost melted during April while in higher altitude (Zone F and Zone G) snow did not melt completely due to presence of permanent snow/glacier ice at low temperature.

The average snow-covered area in the Jhelum River basin derived from MODIS satellite images showed a variation between 5% in the summer and 70% during winter (Fig. 4). The snow/glacier-covered area is more saturated for January 2001 as compared to the January 2017 and the extreme north peripheries also showed the depletion of the SCA. While the summer analysis of the images depicted that July 2017 has spread in SCA towards the south while the concentration of the snow/glacier was effected from 2001 to 2017. These variations existed from the north to south of the basin. The seasonal trend of SCA depicted an increase in SCA during the spring and summer seasons and decreasing trend during autumn while winter showed stability (Fig. 5). Snow cover depletion curve (SCDC) showed a clear picture of SCA in different seasons (Fig. 6). The snow is maximum during January and minimum during July in the Jhelum river basin.

Seasonal studies of the SCA in the basin depicted an increasing trend for SCA for winter and spring while a decreasing trend for summer and autumn. The correlation analysis of temperature and SCA for the period of 2001-2017 illustrated the inverse relationship that depicted an increase in temperature ultimately affecting the melting of snow/glaciers by reducing the SCA (Fig. 7).

The SCA extracted from the MODIS remote sensing data gives the bird's eye view of the basin. The MODIS snow cover product is an efficient way to compensate snow cover area into the snowmelt runoff model to calculate the discharge of the basin. The SCA decreased when there is an increase in temperature due to the melting of the snow. This leads to the deglaciation process by reducing the snow-covered area in the basin. The fastest decline in SCA is the prediction that snow-covered tops and glaciers in the mountainous regions are under threat in terms of depletion due to climate change.

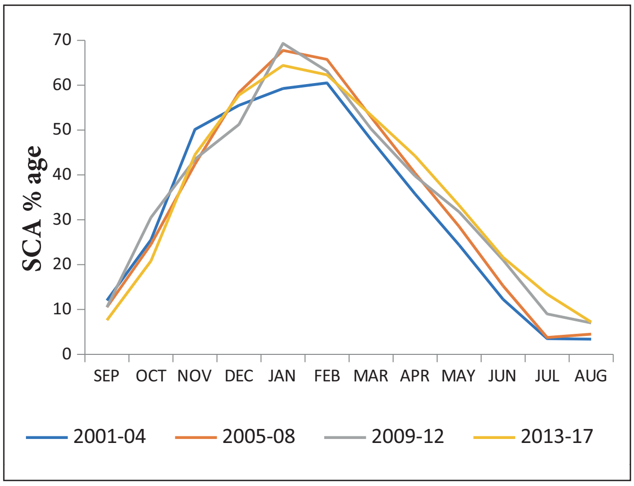

Figure 5. Snow Depletion Curve (SDC) for the Jhelum River basin for the year 2001–2017

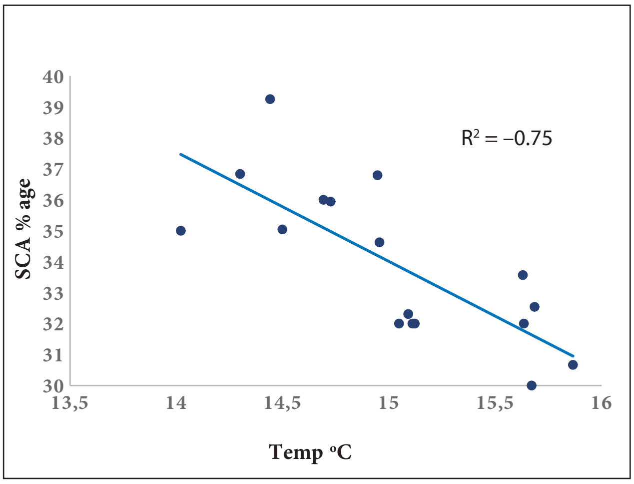

Figure 6. SCA vs temperature (2001-2017)

These snow-covered mountainous tops are the freshwater source for the rivers and low-lying areas. The depletion of these snow-covered tops ultimately leads to a shortage of water in the future.

5. Discussion

The current study focused on the impacts of climate change on snow-covered areas in the transboundary Jhelum River Basin using MODIS satellite data MOD10A2 product. The results revealed that the SCA was impacted in the study region due to temperature changes. The same decline in SCA due to the increase in temperature was observed in Hunza district (Moazzam et al., 2022a). Another study conducted in two valleys i.e. Astore and Shigar contradict the results of this study as in both valleys the SCA is increasing whereas the temperature in both valleys is decreasing (Moazzam et al., 2022b). Furthermore, for more insight the study region was divided into seven zones, based on elevation variation to study the impacts of elevation on the snow cover area and the rate of snow depletion calculated in each zone. The results revealed that in the study region snow depletion starts in March and again starts accumulation in September. The overall variation in snow-covered areas varies from 5% to the lowest depletion time in August and to 70% accumulation during the winter season in February. This high variation in the snow-covered area is due to variations in temperature and precipitation in both the summer and winter seasons. In summer most of the precipitation occurs as rainfall while in winter it is in the form of snow whereas, snow and glacier is sensitive to temperature and play a major role in glacial decrease as well as surging (Banerjee et al., 2021; Moazzam et al., 2022a). Increasing temperatures in the study region especially in the spring season instigates the early snow melting and decrease the rate of snow accumulation which is also reported in other studies (Bolch et al., 2019; Sabin et al., 2020). Changes in snow cover at a higher elevation are comparatively low than the low elevation areas due to temperature difference as high elevated areas have low temperature and receive more snowfall and the same was observed in other studies (Bilal et al., 2019; Moazzam et al., 2022a; Moazzam et al., 2022b).

6. Conclusion

Snow-covered area is the key component of snow/glacial-fed river basins. Climate impacts on the SCA ultimately affect the hydrological dynamics of the river basins. Overall SCA showed seasonal variation between 5% in the summer and 70% during winter for 2001-2017. An increasing trend of snow accumulation for the winter and spring seasons, while a decreasing trend has been observed for the summer and autumn of 2001-2017. The inverse relationship of annual temperature and SCA has been observed that depicted an increased in temperature due to climate change may have adverse effects on the SCA in the future by changing the dynamics of the cryosphere and hydrosphere.

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References

Alexander C., Bynum N., Johnson E., King U., Mustonen T., Neofotis P., Oettlé N., Rosenzweig C., Sakakibara C., Shadrin V., Vicarelli M., Waterhouse J. & Weeks B., 2011, Linking Indigenous and Scientific Knowledge of Climate Change. BioScience 61: 477–484. doi:10.1525/bio.2011.61.6.10

Ali S., Eum H.I., Cho J., Dan L., Khan F., Dairaku K., Shrestha M.L., Hwang S., Nasim W., Khan I.A. & Fahad S., 2019, Assessment of climate extremes in future projections downscaled by multiple statistical downscaling methods over Pakistan. Atmospheric Research 222: 114–133. doi:10.1016/j.atmosres.2019.02.009

Banerjee A., Chen R., Meadows M.E., Sengupta D., Pathak S., Xia Z. & Mal S., 2021, Tracking 21st century climate dynamics of the Third Pole: An analysis of topo-climate impacts on snow cover in the central Himalaya using Google Earth Engine. International Journal of Applied Earth Observation and Geoinformation 103, 102490.

Bilal H., Chamhuri S., Mokhtar M.B. & Kanniah K.D., 2019, Recent snow cover variation in the upper Indus basin of Gilgit Baltistan, Hindukush Karakoram Himalaya. Journal of Mountain Science 16(2): 296–308.

Bolch T., Shea J.M., Liu S., Azam F.M., Gao Y., Gruber S., Immerzeel W.W., Kulkarni A., Li H. & Tahir A.A., 2019, Status and change of the cryosphere in the extended Hindu Kush Himalaya region, [in:] The Hindu Kush Himalaya Assessment, p. 209–255, Springer.

Butt M.J., 2012, Characteristics of snow cover in the Hindukush, Karakoram and Himalaya region using Landsat satellite data. Hydrological Processes 26(24): 3689–3698.

Dankers R. & De Jong, S. M., 2004, Monitoring snow-cover dynamics in Northern Fennoscandia with SPOT VEGETATION images. International Journal of Remote Sensing 25(15): 2933–2949.

Dawood M., Mahmood S., Rahman G. & Rahman A., 2017, Impact of rainfall fluctuation on river discharge in Hindu

Kush Region, Pakistan. Abasyn J. Soc. Sci. 10(November): 246–259.

Dawood M., Rahman A., Ullah S., Rahman G. & Azam K., 2018, Spatio-temporal analysis of temperature variability, trend, and magnitude in the Hindu Kush region using Monte Carlo and Sen's slope approaches. Arabian Journal of Geosciences 11(16): 1–15.

Homan J.W., Luce C.H., McNamara J.P. & Glenn N.F., 2011, Improvement of distributed snowmelt energy balance modeling with MODIS-based NDSI-derived fractional snow-covered area data. Hydrological Processes 25: 650–660. doi:10.1002/hyp.7857. https://nsidc.org/data/modis/.

Immerzeel W.W., Droogers P., de Jong S.M. & Bierkens M.F.P., 2009, Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. Remote Sensing of Environment 113: 40–49. doi:10.1016/j.rse.2008.08.010

IPCC, 2014, IPCC Fifth Assessment Report—Synthesis Report, [in:] IPPC Rome, Italy.

Moazzam M.F.U., Rahman G., Ali K.S. & Lee B.G., 2022a, Spatio-temporal snow cover change in the early twenty-first century using improved MODIS dataset: a case study of District Hunza, Pakistan. Climate Dynamics, p. 1–17.

Moazzam M.F.U., Rahman G., Lee B.G. & Ansari N.A., 2022b, Trend of snow cover under the influence of climate change using Google Earth Engine platform: A case study of Astore (Western Himalayas) and Shigar (Karakoram region). Frontiers in Environmental Science 10: 1–13.

Munawar S., Tahir M.N. & Baig M.H.A., 2021, Twenty-first century hydrologic and climatic changes over the scarcely gauged Jhelum river basin of Himalayan region using SDSM and RCPs. Environmental Science and Pollution Research. doi:10.1007/s11356–021–16437–2

Rafiq M., Li Y.C., Cheng Y., Rahman G., Ali A., Iqbal M., Latif A., Ali I., Rehan A. & Zahoor A., 2022, Spatio-Statistical Analysis of Temperature and Trend Detection in Baluchistan, Pakistan. Ecological Questions 33(3): 1–21.

Rahman G., Anwar M.M., Ahmed M., Ashraf H. & Zafar U., 2017, Socio-economic Damages caused by the 2014 Flood in Punjab Province, Pakistan: Socio-Economic Damages caused by the 2014 Flood in Punjab. Proceedings of the Pakistan Academy of Sciences: B. Life and Environmental Sciences 54(4): 365–374.

Rather M.A., Satish Kumar J., Farooq M. & Rashid H., 2017, Assessing the influence of watershed characteristics on soil erosion susceptibility of Jhelum basin in Kashmir Himalayas. Arabian Journal of Geosciences 10. doi: 10.1007/s12517–017–2847-x

Sabin T., Krishnan R., Vellore R., Priya P., Borgaonkar H., Singh B.B. & Sagar A., 2020, Climate change over the Himalayas. In Assessment of climate change over the Indian region, p. 207–222. Springer.

Saddique N. Usman M. & Bernhofer, 2019, Simulating the impact of climate change on the hydrological regimes of a sparsely gauged mountainous basin, Northern Pakistan. Water (Switzerland) 11. doi:10.3390/w11102141

Sharma V., Mishra V.D. & Joshi P.K., 2012, Snow cover variation and streamflow simulation in a snow-fed river basin of the Northwest Himalaya. Journal of Mountain Science 9: 853–868. doi:10.1007/s11629-012-2419-1

Snehmani Dharpure J.K., Kochhar I., Hari Ram R.P. & Ganju A., 2016, Analysis of snow cover and climatic variability in Bhaga basin located in western Himalaya. Geocarto International 31: 1094–1107. doi:10.1080/10106049.2015.1120350

Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M. & Miller H.L, 2007, IPCC honoured with the 2007 Nobel Peace Prize REPORTS-ASSESSMENT REPORTS IPCC Fourth Assessment Report (AR4) Climate Change 2007: The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on. Lic.Wisc.Edu.

Stocker T.P., Gian K., Tignor M., Allen S., Boschung J., Nauels A., Xia Y., Bex V. & Midgley P., 2013, Contribution of Working Group I to the Fifth Assessment Report of IPCC the Intergovernmental Panel on Climate Change. The Physical Science Basis. doi:10.1017/CBO9781107415324

Tahir A.A., Chevallier P., Arnaud Y. & Ahmad B., 2011, Snow cover dynamics and hydrological regime of the Hunza River basin, Karakoram Range, Northern Pakistan. Hydrology and Earth System Sciences 15(7): 2275–2290.

van Vuuren D.P., Edmonds J., Kainuma M., Riahi K., Thomson A., Hibbard K., Hurtt G.C., Kram T., Krey V., Lamarque J.F., Masui T., Meinshausen M., Nakicenovic N., Smith S.J. & Rose S.K., 2011, The representative concentration pathways: An overview. Climatic Change 109: 5–31. doi:10.1007/s10584-011-0148-z