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ORIGINAL ARTICLE

Climate change and adaptation of mountain societies in Central Asia: uncertainties, knowledge gaps, and data constraints

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Abstract

Mountain societies in developing and low-income countries are highly vulnerable to the impacts of climate change, which can severely threaten their livelihoods. The situation of mountain communities in the Pamir and Tien Shan mountains in Central Asia is exacerbated by remote location, difficult access, and poorly maintained infrastructure as well as by a distinctly continental climate. Designing and implementing climate adaptation policies for mountainous Central Asia is hindered by the limited understanding of a wide range of environmental and socio-ecological parameters. In particular, there are major knowledge gaps on the temperature and precipitation trends in high altitudes of the Pamir and Tien Shan mountains which are the result of poor and frequently unreliable data. These knowledge and date constraints have a negative effect also on forecasting the occurrence and intensity of extreme weather events which constitute a major hazard for local communities residing in the mountain foothills. This study reviews the state of research on climate change and climate change adaptation in mountainous Central Asia, also considering temperature and precipitation projections for the region. This includes an outline of the geophysical and socio-economic conditions of mountainous Central Asia as well as a survey of climate adaptation initiatives and policies currently implemented in the Pamir and Tien Shan mountain region with special consideration of their limitations and challenges. Knowledge gaps and data constraints, especially on climate-glacier-water and hazard interactions, are identified, and research and policy measures are suggested based on the study findings for improving climate change adaptation in mountainous Central Asia.

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Introduction

Mountain communities in developing and low-income countries are vulnerable to constraints imposed by their natural environments and geographic location. Scarcity of natural resources, land degradation, exposure to natural and human-induced hazards, limited infrastructure, and poor communications constitute some of the principle obstacles to achieving sustainable well-being. Climate change has recently been added as a major force which, in association with other hazards and constraints, can severely affect the lives of mountain dwellers. Many studies point towards the fact that mountain people and communities—especially in developing countries—are more susceptible to the negative effects of socio-economic and climatic pressures than lowland communities (Foggin 2016; Heltberg et al. 2010; Heltberg and Bonch-Osmolovskiy 2011; Kohler et al. 2014; Kreutzmann 2001).

The remote communities of the Pamir and Tien Shan highlands of Tajikistan and Kyrgyzstan constitute a typical case of rural agricultural and agro-pastoral people facing adversities, which may be yet further aggravated by climate change. The two mountain complexes are among the highest in the world, with peaks reaching well over 7000 masl, and constitute a continuation of the Himalayas orogenic belt. Within these mountain regions, areas of approximately 10,500 km^2 in the Pamirs and 2300 km^2 in the Tien Shan mountains are covered by glaciers (Alford et al. 2015).

Developing effective strategies and adaptation measures to mitigate the severe impacts of climate change on mountain communities in Central Asia (CA) is a challenging task that requires thorough knowledge of environmental matters and socio-ecological contexts alike. Due to the overall semi-arid conditions of Central Asia, climate change is likely to affect both water and energy balances. Climate processes and the spatio-temporal distribution of climate impacts are especially complex in CA due to the multi-dimensional interactions of the atmosphere with highly dissected mountain topographies, seasonal water regimes, and the variable distribution of people and their livelihood practices (Manandhar et al. 2018). Many of the social-ecological systems in mountainous CA remain poorly understood, largely as a result of limited investment in research and monitoring infrastructure.

Livelihoods among CA mountain societies are precarious not only because of climatic factors, but also due to socio-political factors and forces. Current welfare inequalities in rural communities, including lack of access to basic amenities, are a fact of life for the majority of people living in the region due to an interplay of many factors, of which climate is but one. However, climate change will likely aggravate the existing vulnerabilities caused by a wide range of climatic and non-climatic drivers. Among these, the near collapse of the welfare system, especially in remote areas, following the dissolution of the Soviet Union, ranks very high. Also, due to the dissolution of the Soviet Union, local capacities for weather observation and hazard management were seriously impaired, and most weather monitoring and forecasting and hazard awareness systems have become derelict (World Bank 2016a).

This study sets out with an overview of climate change trends and predictions in CA and elaborates the complex climatic processes occurring in the Pamir and Tien Shan mountains. The following sections address the pronounced social and economic vulnerabilities of mountain societies in CA and present current climate change adaptation initiatives adopted in the region with an emphasis on data and knowledge constraints for the development of climate adaptation measures. Finally, major areas of intervention are identified for the design of better climate adaptation measures and welfare improvement plans for mountain societies of Central Asia.

Mountain regions of Central Asia

The term Central Asia is applied in the context of this study to the countries of Kazakhstan, Kyrgyzstan, Turkmenistan, Tajikistan, and Uzbekistan, which have become independent nations after the dissolution of the Soviet Union. They share a common political experience, as well as similarities in cultural, environmental, and economic terms to varying degrees. We will concentrate on Kyrgyzstan and Tajikistan which are characterized by the largest proportion of mountainous terrain and include the adjoining mountainous regions of Afghanistan, Pakistan, and China. Another reason for focusing on Kyrgyzstan and Tajikistan is that they have been identified as the most climate-vulnerable countries of the former Soviet Union (Fay and Patel 2008).

The majority of mountain societies of CA resides in the Pamir and Tien Shan mountainous ranges. The Pamir mountains culminate in the complex *Pamir Knot* which is centered in the southeast region of Tajikistan in Gorno-Badakhshan Autonomous Oblast (GBAO) (province). The northern part of the Pamirs connects with the Tien Shan mountains of Kyrgyzstan, the southern part with the Hindu Kush mountains in Afghanistan and Pakistan. The eastern part of the Pamirs lies in far western China, while the western part extends into northeastern Afghanistan. The Pamir region includes some of the highest peaks in the world, with summits over 7000 masl, and an average elevation between 4000 and 5000 masl. The Tien Shan mountains form one of the longest mountain ranges in the world (2800 km). The western portion of the Tien Shan mountain range is situated in Kyrgyzstan, extending also to the Kazakh-Kyrgyz border region, while the eastern ramparts transect much of Xinjiang Uygur Autonomous Region (province), China. Elevations are lower than those of the Pamirs, with the majority of sub-ranges situated at 3–4000 masl (Farinotti et al. 2015).

The Pamir and Tien Shan ranges and their mountain societies are subject to a unique set of environmental, social, political, and economic conditions that play out and combine at multiple temporal and spatial scales. Situated in the interior of the Eurasian land mass and blocked off by the mountain ranges of the Hindukush and western Himalayas in the south which prevent inflow of humid air from the Indian Ocean, Central Asia has an arid to semi-arid continental climate. Summers are hot and dry; winters are moist and relatively warm in the south and cold in the north (Zomer et al. 2015). The big rivers of the region—the Amu Darya and the Syr Darya—are glacier- and snow-fed to a large extent and drain into endorheic basins such as the Aral Basin. Glacier and snow melt compensate for summer aridity by providing a lot of the water that is required for irrigated agriculture. Forest cover comprises 5% or less of the total land area on account of the dry climate, deforestation, and forest degradation. Natural vegetation consists mainly of grassland and scrub (Yin et al. 2017).

Mountain communities in Central Asia are culturally heterogeneous. The dominant groups are speakers of Turkic and Persian-descent languages, but there is a plethora of other ethnicities including Russians, Chinese, and Koreans, to name but a few. The majority of mountain communities is engaged in subsistence farming and livestock husbandry. In many parts of mountainous Central Asia, livestock keeping was carried out in the nomadic tradition, especially by people of Turkic descent such as the Kyrgyz, with a focus on sheep, goats, and horses. While the nomadic tradition was broken by the sedentarization campaigns of the Soviet period, livestock keeping based on transhumance between summer and winter pastures is still an economically and culturally important livelihood activity.

Subsistence farming is peripheral in regions, where livestock keeping predominates, often limited to small home gardens, and marginal in those mountain areas where it provides the mainstay of people, such as in large parts of the Tajik Pamirs. There, farming is restricted to river oases or to small patches of irrigated land on steep slopes. Another limiting factor is the scarcity and poor quality of soil in a landscape dominated by rocks and scree slopes. The main crops grown are wheat, barley, potatoes, pulses, and fruit trees, and the average farm size is 0.08 ha (Shenhav and Domullodzhanov 2017). In response to these marginal conditions and initially triggered by the economic collapse that followed in all countries of Central Asia upon the dissolution of the Soviet Union, there is a large migration mainly of young people to the Russian Federation and increasingly also to other countries (Diagne et al. 2014). While remittances from these migrants are an important contribution to livelihoods in the source areas, especially when these are located in mountains, it appears that only a small portion of these is invested productively in improving land use practices (Freedman and Neuzil 2015; Lioubimtseva and Henebry 2009; Sagynbekova 2017).

Other legacies of the past that, apart from the consequences of the economic collapse following independence, continue to affect the lives of mountain communities include weak customary institutions and disappearance of formal regulatory institutions, and environmental degradation (Dong et al. 2011; Kreutzmann 2001). Pastoralism, especially, is affected by the transition from collective to communal management of pastures which is hampered both by the still persisting Soviet legacy and the immaturity of new institutions such as the Pasture Management Committees (Isaeva and Shigaeva 2017). This results in continuing degradation of pastures as one of the major environmental problems in mountainous Central Asia. The use of water resources, now gradually delegated to Water User Associations as a local institutional scheme, is affected by similar problems.

The Kyrgyz and Tajik government structures are characterized by centralized and hierarchical decision-making with increasingly authoritarian elements as well as by inadequate consideration of the specific needs of remote regions like mountain areas in national policy processes. Political and economic deprivations have led to social and political tensions. In Tajikistan in particular, the southeastern Gorno-Badakhshan Autonomous Region (GBAO) is described by a volatile security situation, exacerbated by proximity to the border with Afghanistan. But also in Kyrgyzstan, mountain regions have witnessed violent protests (ENVSEC - Environment and Security Initiative, 2017).

The relations of Central Asian governments are often present lack of regional integration despite the need for cooperation on management of joint resources such as, e.g., water, and their desire to pursue their own national development agendas. Competing claims over water resources between upstream and downstream countries, as for power generation in Kyrgyzstan and Tajikistan, and for irrigation in Uzbekistan, have been the cause of severe intergovernmental conflicts in the past and require more dedication towards regional cooperation. Currently, water stresses seem to be a consequence of management deficits and lack of investments in infrastructure development rather than of water scarcity (Hill et al. 2017). The drying out of the Aral Sea is the most conspicuous result of these management and cooperation deficits (Xenarios et al. 2018).

This short introduction to mountainous Central Asia is meant to highlight that there is already a high level of regional vulnerability that is due to non-climatic factors, such as poverty, environmental degradation, weak governance, extensive migration, and lacking regional integration, and which is likely to be exacerbated by climate change.

Climate change in mountainous Central Asia

Central Asian mountains are sensitive to climate change due to, among others, enormous storage of water resources as glaciers and snow at high altitudes. Glaciers are an indispensable resource of water for mountain communities but also for downstream populations as they contribute significantly to late summer discharge when aridity reaches peak levels. Moreover, snowmelt is the main river flow component in the mountains of Central Asia and decisive for seasonal water availability. Past studies on the assessment of climate change have reported varying results depending on underlying data conditions. These changes also vary geographically. Lioubimtseva et al. (2005) reported a general warming trend in CA in the order of 1–2 °C since the beginning of twentieth century. Another study by Mannig et al. (2013) reports a warming magnitude of above 3 °C in CA with some regions exceeding 5 °C when comparing the 2071–2100 mean to the 1971–2000 mean.

When focusing on the mountainous regions, the mean annual temperature in the northern Tien-Shan below 2000 masl appears to have increased by 0.006 °C $year^{-1}$ from 1940 to 1990 while the annual mean precipitation presumably has increased by 100 mm during this period (Aizen et al. 1997). Kriegel et al. (2013) observed an increasing trend of mean summer (April–September) temperature by 0.19 °C/decade over the period from 1960 to 2007 for Naryn town (2041 masl), located in the inner Tien Shan mountains. For the winter months, more pronounced warming has been detected at higher elevations of the Tien Shan range (Kriegel et al. 2013; Mannig et al. 2013). No statistically significant trend has been revealed for precipitation in the same area and during the same period. Unger-Shayesteh et al. (2013) reviewed climate change studies in CA mountains and reported a wide range in mean annual temperature trends between − 0.1 and + 0.6 °C per decade in the Tien-Shan (using 30 stations) and Pamir (using 5 stations) mountains. The review agreed on less pronounced warming trends at higher altitudes and in protected intramontane valleys compared to lowlands.

Despite the current research on climate trends in mountainous CA, our knowledge is still incomplete in particular regarding the magnitude and the spatio-temporal patterns of changes in CA headwater catchments. The scarcity of studies on climate change assessment is especially pronounced in the Pamir mountains and can be due to limited data availability.

Climate change in mountainous CA is believed to have a strong effect on the hydrological cycle, especially in regions with snow and glacier melt-dominated freshwater sources (Barnett et al. 2005; Hill et al. 2017). Future climate warming will cause snowmelt to occur early in the spring months leading to frequent flood hazards. Accelerated glacier melting, which is already widely observed and documented (Farinotti et al. 2015; Hagg et al. 2013a; Kriegel et al. 2013; Narama et al. 2010; Sorg et al. 2012) will have negative consequences for water availability in the late summer months when water resources in CA are needed for agricultural production in the downstream regions. Peak runoff is likely to shift from July to June, although catchment-specific climate change models do not exist for most of CA. The exception is a study of the Pandj basin, which foresees that a peak runoff will be reached between 2060 and 2080 (Kure et al. 2013), assuming a modeled warming scenario of 2° to 4 °C. Lioubimtseva and Henebry (2009) reported in their analysis a temperature increase by 3–5 °C until 2080. Their analysis of precipitation data, however, shows contradictory results and insignificant changes.

Precipitation projections by Reyer et al. (2017) exhibit a southwest–northeast gradient for CA—with precipitation increasing from south-west to north-east. The authors, however, point out that their projections are fraught with a high degree of uncertainty due to the use of global circulation models (GCMs) that may insufficiently reproduce CA precipitation patterns. Furthermore, these predictions were conducted for the entire CA region without focusing on its mountainous parts. Despite these uncertainties, adaptation measures to changes in the hydrological cycle need to be considered when developing strategies for the future (Hill et al. 2017).

The above-mentioned studies are based on data from meteorological stations at different geographic locations. However, limited data is available in mountainous areas where studies based on only a few observations may not be valid for the entire region. In order to draw a more integrated profile of climate change predictions in Central Asian mountains, we employ the Coupled Model Intercomparison Project (Coupled Model Intercomparison Project (CMIP5), 2017) to assess future climate changes in the Tien Shan (Naryn Basin) and Pamir (Pandj) mountains until 2095. We used an ensemble of climate model simulations from CMIP5 (Taylor et al. 2012), which are available from 1951 until 2099. A total of 30 climate model outputs were entered, which delivered daily precipitation and temperature data. The CMIP5 climate data were obtained from the data portal of Deutsches Klimarechenzentrum GmbH (esgf-data.dkrz.de) for the Tien Shan and Pamir mountains.

The current study adopted the Representative Concentration Pathways (RCP) of 2.6 (radiative forcing at about 2.6 W/m^2 before 2100 and decline), 4.5 (stabilization of radiative forcing to 4.5 W/m^2 before 2100), and 8.5 (Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100) to develop temperature and precipitation predictions. The RCP 6.0 scenario was not considered since it was simulated by very few climate models.

The data analysis was done by averaging all grid values covering the Tien Shan (Naryn watershed) and Pamir (Pandj river watershed) mountains (Fig. 1) for each day, leading to daily time series for both catchments in the period of 1951–2099 for each model run. Spatially distributed information for the covering of the whole mountain range may give more representative variation of regional climate despite the course spatial resolution.

We chose four periods of 30 years each to quantify changes in climate as of 1990s, 2020s, 2050s, and the 2080s. The ensemble of 30 daily climate scenarios obtained for Tien Shan and Pamir was aggregated to annual mean temperature (in °C) and annual precipitation (in mm). The ensemble of aggregated annual values was then used to estimate means for each time 30-year interval. The mean values for each time frame represented the temperature and precipitation trends in the study areas.

Figure 2 shows the potential variations of temperature and precipitation in the adopted time-frames for both mountain systems.

A temperature increase by about 1.8 °C relative to the 1990s is discernible in the Tien Shan mountains already in the 2020s (considering average of ensemble medians for RCP2.6, RCP4.5, and RCP8.5). In the Pamir mountains, the change in temperature during this period is less pronounced with about 1.4 °C difference. The changes in temperature between 2020s and 2050s are not as pronounced as those from the 1990s to the 2020s in the Tien-Shan with a temperature increase of 0.9 °C. Temperature differentiation appears to be more distinctive in the Pamir mountains with about 1.4 °C temperature increase in the same period. The results of climate change analysis show that until 2020, temperature increase is more evident in the Tien-Shan than in Pamir, while it becomes obvious in Pamir between the 2020s and 2050s. Temperature change between the 2050s and the 2080s is negligible, except for the RCP8.5 scenarios which represent more extreme conditions than other scenarios (RCP2.6 and RCP4.5). Future trend of precipitation in both mountain systems is characterized by unclear variability. The ensemble range is higher in the Pamir than in the Tien Shan mountains which may indicate higher uncertainty of precipitation changes.

Climate change policies and challenges in mountainous Central Asia

Responding to the climate change challenges in mountainous CA, both national governments as well as regional and international actors have made efforts to strengthen the adaptive capacities of mountain societies in CA. While there are several studies on climate change adaptation (CCA) policies and practices in Central Asia in general (see, e.g., Ford et al. 2015; CAREC 2011, 2013; Christmann and Aw-Hassan 2011; Fritzsche et al. 2011; Sorg et al. 2012; Souza et al. 2015; Thomas 2008), there is much less literature on CCA policies focused particularly on Central Asian mountain regions (see, e.g., Ashley et al. 2015; Hall 2014). Our interest therefore is the implementation of CCA policies that focus on local capacities in mountain regions of CA as well as those that specifically target mountain areas across borders at regional level.

Both Kyrgyzstan and Tajikistan have adopted key legislative documents and policy strategies on climate change adaptation by identifying priority sectors such as disaster risk reduction and sustainable development[1] while institutional structures and coordination mechanisms were established[2] (ENVSEC - Environment and Security Initiative, 2017). These documents and several other studies and reports (CAREC 2013; Fay et al. 2010) highlight a range of adaptation measures that have been selected to reduce vulnerability in priority areas, focusing mainly on water and agricultural sectors. The Government of the Kyrgyz Republic has developed sectoral CCA programs for five priority sectors: agriculture, water resources and energy, emergency situations, health system, forests, and biodiversity. Especially relevant for mountain regions are the efforts directed towards integrated water and pasture management as well as towards forests and biodiversity.

To achieve these objectives, different activities were implemented, such as pasture management plans elaborated by Pasture Committees (the executing bodies of Pasture User Unions (PUUs) at sub-district level), taking climate change into account. Indicatively, one of the CCA actions is to decrease livestock load on pastures by 10–30% during harsh climatic events (World Bank 2016b). However, despite good intentions, such adaptation measures may not always be feasible. For instance, animals cannot be taken off pastures during extreme weather, because there is not enough forage stored at the household. Other adaptation measures mentioned in pasture management plans, e.g., irrigation of seasonal pastures and haymaking plots, sowing of forage crops on pastures, fencing pastures, and forest plantations, also face obstacles due to lack of adequate resources (financial, human, time) as well as lack of knowledge and expertise. Some of the problem gaps affecting CCA implementation at community level in pasture regions are dealt with by the Community Development and Investment Agency (ARIS). ARIS is the key governmental organization aiding Pasture Committees and local authorities in rehabilitation projects, capacity development, and contributing to the realization of pasture management plans.

[1] These include, among others, the Kyrgyz Government Resolution #549 on the Priority Directions for Adaptation to Climate Change in the Kyrgyz Republic till 2017, issued in 2013, and the Tajik *National Action Plan for Mitigation of Climate Change Consequences* issued in 2003 (which includes a strategy on climate change adaptation) as well as a *State Program on Monitoring and Conservation of Glaciers until 2020*. Both countries also have adopted National Strategies on Sustainable Development.

[2] In Kyrgyzstan, these include the Climate Change Coordination Commission, chaired by the First Deputy Prime Minister, and the Centre on Climate Finance; in Tajikistan the Secretariat of the Pilot Program for Climate Resilience (PPCR) funded by the Asian Development Bank for coordinating all the climate change related projects (ENVSEC 2017:53, World Bank 2017, PPCR 2017).

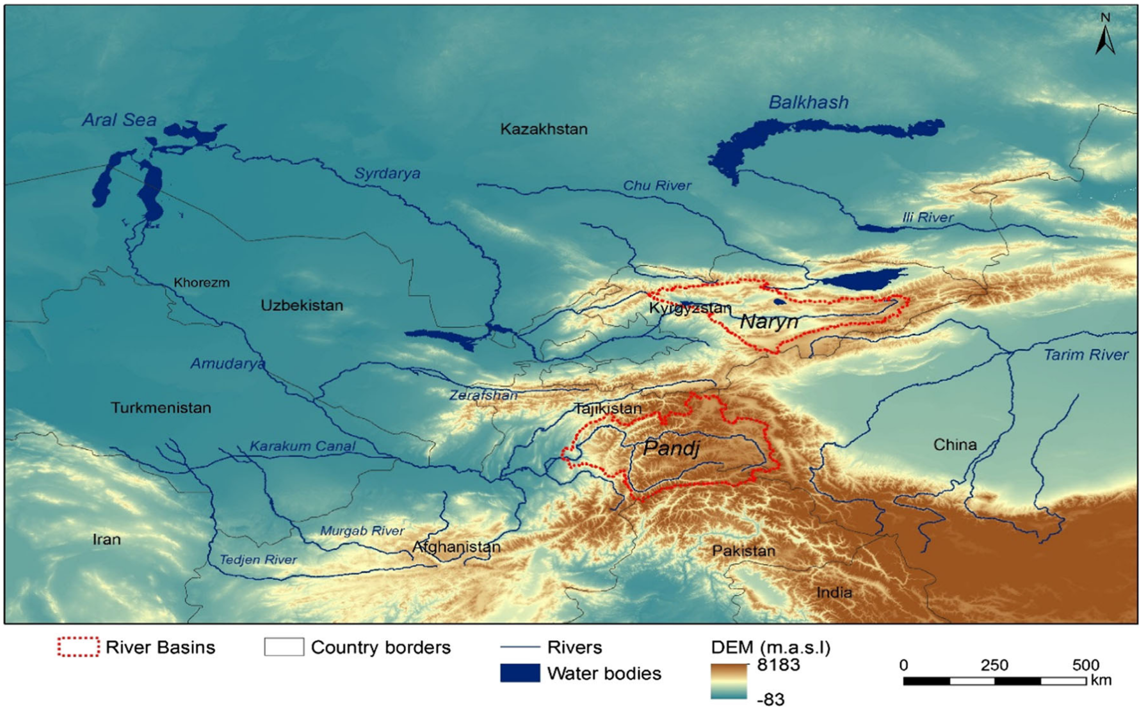

Fig. 1 Central Asian domain with Naryn and Pandj basin as representative areas for the Tien Shan and Pamir mountain systems (about here)

A recent initiative of the Ministry of Agriculture is the establishment of the Public Seed Funds under the PUUs to satisfy local needs for climate change-resilient grain and forage crops; however, the impact of this initiative to date remains uncertain (MoA 2018). In the water sector, the Kyrgyz government focuses its CCA policies on the rehabilitation of water irrigation infrastructure and introduction of water-saving technologies such as drip irrigation. Although the rehabilitation of water irrigation infrastructure receives financial support of different international organizations, the coverage of mountainous regions by this scheme is less than 30% overall. The major impediments are the high capital and maintenance costs and the technical knowledge required for its operation (Department for Water Resources and Land Reclamation of Kyrgyzstan 2018).

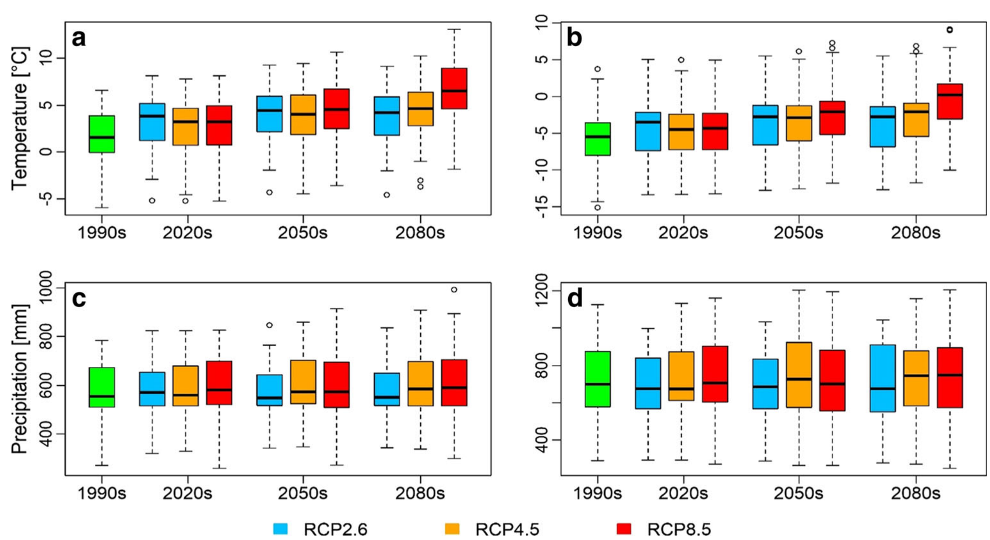

Fig. 2 Future changes in mean annual air temperature for Naryn (**a**) and Pandj (**b**) and annual precipitation for Naryn (**c**) and Pandj (**d**) based on IPCC CMIP5 Representative Concentration Pathways (RCPs), RCP2.6, RCP4.5, and RCP8.5. Each boxplot represents the ensemble scenario range (about 30 model outcomes depending on availability of model runs for each RCP) of 30-year mean values (for 1990s: 1976–2005, for 2020s: 2006–2035, for 2050s: 2036–2065, for 2080s: 2066–2095). Only models with daily simulation step were considered. The black lines inside each boxplot represent median of ensemble scenarios (about here)

In Tajikistan, the State Committee on Environmental Protection plays a key role in facilitating and implementing programs and projects on climate change adaptation. Sustainable water management and disaster risk reduction are among the priorities of the Tajik government, which is also reflected in the implementation of CCA policies at local level. In this respect, the government as well as international actors see the development of water user associations (WUAs), which has been promoted since the early 2000s, as an approach for CCA in Tajikistan. Many of the WUAs are still far from being fully functional institutions, with only few successful examples. However, the successful cases seem to follow a mixture of traditional and novel practices that have increased the access to irrigation also under conditions of weather extremes (Shenhav and Domullodzhanov 2017).

Other initiatives mainly driven by international donors are concentrated on the capacity building of mountain communities in the field of natural resources management. Indicatively, a major initiative is the "Environmental Land Management and Rural Livelihoods Project" implemented with the support of World Bank and Global Environmental Facility (World Bank 2018a). Interactions with many stakeholders have identified the need of local farmers to increase pasture productivity through sowing of perennial plants, agroforestry, and building of greenhouses. A new initiative supported by the Green Climate Fund on "Building climate resilience of vulnerable and food insecure communities through capacity strengthening and livelihood diversification in mountainous regions of Tajikistan" (2018–2022) aims to enhance sustainable water management, resilient agriculture, and forestry as well as capacity building on disaster risk preventions with as yet unknown results (Green Climate Fund 2018). Disaster risk management and prevention have been in the spotlight of many donor-supported projects in cooperation with local mountainous communities. Different activities were conducted like small-scale infrastructure improvements (e.g., construction of flood protection walls), developing evacuation maps, constructing shelters, and training of volunteers for the search and rescue brigades (World Bank 2018b). However, such examples still wait to be scaled up to the majority of vulnerable regions.

Another CCA project targeting CA mountain areas is the "Ecosystem-based Adaptation (EbA) to climate change in the high mountain areas of CA" project funded by Germany's International Climate Initiative (IKI 2016) for setting up a framework for participatory analysis of climate change and adaptation measures. Another noteworthy initiative is the Global Snow Leopard & Ecosystem Protection (GSLEP) Program, funded by a range of agencies, which, by focusing on one specific species, provides a forum to promote the protection and sustainable use of high mountain ecosystems by means which include a strong component of CCA measures (Liebenguth, 2017).

Some regional frameworks have supported the resilience of mountain territories in CA through a number of initiatives. Most notable are the Regional Mountain Centre (RMCCA), the Alliance of CA Mountain Communities (AGOCA), and the CA Mountain Hub (CAMH). Both the AGOCA, an association of currently 66 mountain villages in Kazakhstan, Kyrgyzstan, and Tajikistan, and CAMH are following a "member to member" approach where person-to-person exchanges help to build capacity of local people and organizations for adaptation to climate change through sharing of experiences and mutual learning (Central Asian Mountain Hub (CAMH), 2017). Their CCA initiatives contributed to, for example, successfully solving long-term problems of drinking water and irrigation water shortages and diversification of income generation activities (yak milk, wool, and felt processing) for remote mountain communities in Kyrgyzstan. They enable dissemination of best practices, mutual learning, and application of sustainable practices for climate change adaptation by representing a suitable mechanism for regional partnership and collaboration (Manandhar et al. 2018).

A project supported by the Swiss Agency for Development and Cooperation and CAMH on "Traditional practices on climate change adaptation in Central Asia" has actively encouraged the documentation, dissemination, and preservation of local traditional and innovative technologies, knowledge, and practices related to CCA in mountain communities of Kyrgyzstan, Tajikistan, and Kazakhstan. The project results show that many communities have a long history of coping with different environmental challenges. However, the magnitude of current changes may exceed their traditional coping capacity (AGOCA 2017). This is exacerbated by the unavailability of and inaccessibility to new mitigation and adaptation practices and technologies (e.g., concrete dams against river bank erosion).

Despite a continuous effort combating climate change in mountainous CA, the point has been made that adopted measures often lack the necessary scientific underpinning. Without a sound understanding of quantitative assessments and probability considerations, mountain communities may risk lower coping capacity to climate change in the long run (Jones et al. 2012).

Climate-glacier-water and hazard interactions: knowledge gaps and data constraints

Climate and glaciers

Accumulating knowledge about climate change and climate change adaptation of mountain communities in CA is slowly gaining momentum (Aus der Beek et al. 2011; Bobojonov and Aw-Hassan 2014; Feng 2013; Hagg et al. 2013b; Hewitt 2007;

Malsy et al. 2012; Oberhansli et al. 2011; Qi et al. 2012; Reyer et al. 2017; Robinson et al. 2010; Savitskiy et al. 2008; Sommer et al. 2013; Thomas 2008; Zhumanova et al. 2016). However, research and development activities in the field of climate-glacier-water interactions and their relations to risks and hazards are still limited. In particular, climate scenarios are frequently fraught with uncertainty due to scant and unreliable data on temperature and precipitation trends in high altitudes (i.e., above 3000 m) of the Tien Shan and Pamir ranges (Alford et al. 2012).

Existing hydro-meteorological stations in Tajikistan and Kyrgyzstan are mostly derelict, and maintenance is inadequate due to the lack of spare parts. Until the end of the Soviet era in 1991, there was an extensive network of meteorological and hydrological stations and other facilities, most of which are now out of service. Indicatively, the number of meteorological stations in Kyrgyzstan has been reduced to nearly one third since 1985, while the hydrological stations in both Kyrgyzstan and Tajikistan have been reduced by half (World Bank 2016a). Wind measurements were halted completely after the dissolution of the Soviet Union, and the snow surveys that were carried out prior to the 1990s have also ceased. During Soviet time, selected glaciers were monitored in Tajikistan and Kyrgyzstan with annual glacier mass balance measurement campaigns. These activities have also ceased after independence.

Some meteorological stations operating before the 1990s at altitudes above 3000 masl have fallen into disrepair. Currently, there are only a few stations at high altitudes which makes it difficult to assess climate change impacts on mountain environments. Indicatively, the permanent Abramov station at an elevation of about 4000 masl was destroyed in 1999 and the observations were discontinued. Only recently, some automatic weather stations were installed in mountainous regions (Schöne et al. 2013) and repeated annual observations of selected glaciers were re-established (Hoelzle et al. 2017). The weather and forecasting facilities and related capacities in the hydro-meteorological agencies of both Kyrgyzstan and Tajikistan (Kyrgyzhydromet and Tadjikhydromet) cannot meet the operational standards of the World Meteorological Organization. An overhaul of the hardware system is necessary to extend the monitoring network of meteorological observations. Due to the scarcity and dysfunctional status of weather stations, the temperature record in Tien Shan and Pamir highlands relies largely on measurements taken in lowland stations and extrapolated to adjacent areas. Air temperature for glaciated zones is inferred through different technical proxies which may entail a deviation of up to 50% from actual temperatures. In the case of precipitation measurements at high altitudes, a statistical error of up to 30% of actual intake can be expected (Savoskul and Smakhtin 2013).

The effects of climate change on Tien Shan and Pamir glaciers are nowadays approached through assessment techniques such as satellite gravimetry, laser altimetry, and glaciological modeling to reduce uncertainty factors (Farinotti et al. 2015). It is acknowledged, however, that parameters such as the energy exchange from solar radiation through short- and long-wave energy sources is a major determinant of glacier mass balance which has been insufficiently explored (Savoskul and Smakhtin 2013). There is also scant knowledge of the debris thickness and its role in the glacier retreat in warm periods. Further, the wind-driven redistribution of snowfall on glaciers as well as on the amount of dead ice and active rock glaciers in the Tien Shan and Pamir mountains is still poorly assessed. Knowledge of glaciological features (e.g., topography, gradient) of Tien Shan and Pamirs that is stored in national inventories of Tajikistan and Kyrgyzstan is outdated and information after the early 90s is mostly missing.

Hydrological constraints

The interaction of glacier melting with the hydrological regime in the study area has been explored in selected river basins (Aizen et al. 2007; Diagne et al. 2014; Hagg et al. 2013a, 2013b; Gan et al. 2015; Kriegel et al. 2013; Kure et al. 2013; Mergili et al. 2013; Salamat et al. 2015; Stucker et al. 2012; Wang et al. 2013; White et al. 2014). Estimating snowmelt and glacier melt discharge into river basins of the Pamir and Tien Shan is, however, a very challenging task that requires spatio-temporal analysis of precipitation intake in mountainous areas in conjunction with the analysis of discharge amounts in river basins. The extensive and complex network of river basins in CA mountains complicates the estimation of water runoff due to significant differences in the contribution of snow and glacier melting to various stream outlets (Hill et al. 2017; Hock 2005). Abandoning after the dissolution of the Soviet Union the few gauging stations that had existed in the highlands has made it almost impossible to precisely measure the water runoff into the basins of CA rivers.

The overall poor standards of data collection and low quality of precipitation and discharge data have restrained the development of reliable hydrological models that could more effectively predict the effects of ice and snow melting and contribute to an improved understanding of the occurrence of hazards. Most of the hydrological models applied in CA basins rely on “rainfall–runoff” or “black box” correlation modeling, where the precipitation input is correlated with streamflow output for the estimation of water volume and its fluctuations on a basin level (Alford et al. 2015). These models, however, generally fail to identify whether precipitation input is derived from rain, snow, or glacier melt.

A new method—the isotope fingerprinting technique—has been recently introduced for tracing of and differentiating between snow and ice-melt components. Indicatively, a study has successfully investigated the glacier melt, snow, and rainfall contributions to the Naryn river runoff using a promising "isotope fingerprinting" method (Hill et al. 2017). Also, different remote sources are now used such as satellite imagery, global databases, and global circulation models, to better assess seasonal water availability forecasting (Apel et al. 2018; Gafurov et al. 2016; Kalashnikova and Gafurov 2017). These new tools and techniques enhance the reliability and precision of water balance assessments by considering the evolution of extent and spatial distribution of snow cover for forecasting purposes instead of precipitation input from a single point (e.g., meteorological station) which is spatially highly sensitive. Nevertheless, these sources cannot accurately calculate precipitation amounts and thus can be a cause of misinterpretations of the possible hazards generated by hydrological causes.

Hazards and community vulnerability

Due to the knowledge vacuum on climate-glacier interactions presented above, it is difficult to predict hazards triggered by extreme weather events, like flash-floods, landslides, and Glacier Lake outburst floods (GLOF). A recent study has emphasized that both Kyrgyzstan and Tajikistan suffer from Extreme Hydro-meteorological Hazards (EHHs) (World Bank 2016a). As noted "Meteorological, agrometeorological, and hydrological events are classed as EHHs when by intensity, territorial coverage (more than 30 percent of the region's territory), or duration they could cause or have caused significant damage to the economy and population and could result or have resulted in a disaster".

Table 1 presents the average annual frequency of EHHs in both countries and the related costs in monetary terms (US$). As shown in this table, floods and mudslides are the most frequent hazard types in both Kyrgyzstan and Tajikistan. Most of the hazards occur in mountainous regions, devastating the economic foundations of local societies and endangering human lives. Though the occurrence of droughts may be less frequent, their economic impacts—mostly in the form of losses in agricultural production—are disproportionally high. Other hazards met frequently in the highlands of CA are rainstorms, snowstorms, windstorms, and avalanches. Although the accumulated economic impact of these latter hazards may be significantly lower on a national level than that of floods and landslides, locally the occurrence of avalanches (for instance) has repeatedly threatened human security in mountain regions by damaging vital infrastructure such as roads and bridges.

On the other hand, the vulnerability of local communities cannot be ascribed only to hazards, as has been done in some studies and development projects in mountainous CA (Broka et al. 2016a,b; Diagne et al. 2014). To distinguish between the contributions of pre-existing social deprivations and climate-induced hazards to community vulnerability is a complicated and multi-dimensional task. The livelihoods of CA mountain societies are precarious not only because of climatic factors. Current welfare conditions and inequalities in rural communities and lack of access to basic amenities are still a fact of life in many parts of CA due to an interplay of many factors, of which climate is only one (Mogilevskii et al. 2017). Climate change is likely to aggravate existing vulnerabilities which are caused by a wide range of climatic and non-climatic drivers (Manandhar et al. 2013; Xenarios et al. 2016). A detailed assessment of vulnerabilities would require a comprehensive technical and

Table 1 Average annual frequency of occurrence of major extreme hydro-meteorological hazards in 2008, and the annual average economic losses (US Dollars in 2006 prices) connected with them

Type of event	Kyrgyzstan		Tajikistan	
	Frequency of occurrence (annual)	Average annual economics losses (M US$)	Frequency of occurrence (annual)	Average annual economics losses (M US$)
Floods and landslides	43	11	42	11.7
Drought	0.5	7.3	0.12	7.6
Spring and autumn frosts	2	7.5	n/a	n/a
Severe storms	n/a	n/a	1.1	0.4
Rainstorms	5.6	0.4	3	1.5
Hail	1.6	0.5	7.7	1.6
Snowstorms	2.6	0.2	3	0.6
Avalanches	15.1	0.3	26.6	0.8
Windstorms	4.5	0.1	8.1	0.8

Source: World Bank, 2016a

M US$ Million US Dollars in 2006 prices, *n/a* not available social analysis, which so far has not been conducted. The interplay of climatic and non-climatic drivers should be further investigated to better evaluate the effect of climate and weather extremes on the mountain societies of CA.

Research and development initiatives

There are several initiatives by national authorities and donors to enhance adaptive capacity of mountain communities in the Tien Shan and Pamirs as noted in Section 4. However, the knowledge constraints on climate-glacier-water interactions and hazards often result in the limited and ineffective implementation of targeted projects and wider regional programs. A framework of research and development measures with a specific focus on climate, glacier, and water aspects is proposed and shown in Table 2. The table also includes suggested interventions to better facilitate hazards and improve adaptive capacity.

From a research perspective, climate modeling scenarios with higher resolution for the mountain landscape of Tien Shan and Pamirs should be developed to gain better understanding of climate trends at smaller (local) scales (Rangwala and Miller 2012). Better knowledge of glacial physiography and of the hydrological regime in the major river basins of mountainous CA is essential for improved climate modeling in the study area. That presumes intensified monitoring of glaciers through on-site measurements and remote sensing approaches by also updating the inventories and repositories with relevant data (e.g., topography, gradient). In parallel, hydrological modeling should be further improved by more precise estimations of precipitation amounts, the forms of precipitation, multi-objective calibration, and the energy exchanged between glaciers and downstream portions of regional river basins. Better evidence and probabilistic forecasting arising from regional climate scenarios and hydrological models could significantly assist in the development of risk and hazard mapping for the mitigation of community vulnerability in mountainous CA (Borga 2013). The vulnerability status of communities should be assessed in more depth by distinguishing between climatic and non-climatic factors or drivers, which determine vulnerability. There are existing regional mountain frameworks as shown in Section 4 (e.g., RMCCA, AGOCA, and CAMH) that could upscale CCA initiatives, also by engaging better with local society.

Some development and infrastructural interventions should be introduced to enable the effective accomplishment of the above research and knowledge initiatives as shown in Table 2. A denser network of hydro-meteorological stations to be set up particularly in high altitudes (3000 masl) is a necessary precondition for the better understanding of climate-glacier-water interactions in CA mountains. Establishment of automated weather stations in high altitudes of glaciated zones (Hoelzle et al. 2017) has demonstrated in an exemplary fashion the significance of these installations for the development of climate scenarios. More importantly, the online data transfer to local mountain communities has been proven vital for the mitigation of natural disasters caused by extreme weather events. Early warning systems have been set up along weather stations in fragile ecosystems like glacial lakes to provide timely warning to surrounding communities of the possibility of Glacier Lake Outburst Floods (GLOF) and of the occurrence of debris flows.

There are allegations, however, that automated weather stations may be unsuitable in remote and harsh environments of high mountainous ranges (Alford et al. 2012) as often; these sophisticated devices may become dysfunctional due to natural calamities (e.g., avalanches). The repairing or supplying of spare parts by regional or national authorities is unlikely to happen due to lack of knowledge on the maintenance of such advanced weather systems. It is proposed instead that simple manual weather data collection devices should be installed where the restoration in case of malfunction could be accomplished through local support. In parallel, the local communities shall undertake the data collection and monitoring of these stations through capacity building trainings. Involving local population in monitoring the main drivers of natural disasters can provide a sense of communal responsibility with a direct role in the management of natural hazards.

Economic mechanisms and tools for establishing (co-creating) better adaptation strategies should also be shared and understood by communities, providing a basis for longer-term development partnerships and solutions.

Table 2 Suggested interventions for improving climate adaption in mountain Central Asia

Initiatives	Climate	Glacier	Hydrology	Hazard mitigation	Adaptive capacity
Research	Downscale climate scenarios	Glacier monitoring	Hydrological modeling and precipitation	Risk and hazard mapping	Climate vs non-climate drivers
	Inventory of glacier features (e.g., topography, gradient)			Community role in decision processes	
Development	Hydro-meteorological stations in high altitudes (> 3000 masl)			Community-based early warning systems	
	Capacity building and weather data collection Data-sharing from hydro-meteorological agencies			Economic and finance tools in promoting CCA and Disaster Risk Reduction (DRR)	
	High-impact market interventions, multipurpose projects				

Community-led initiatives such as the introduction of more resilient crops or better livestock and rangeland management regimes presented in Section 4 could be enhanced, based on purposeful, strategic fusion of traditional knowledge and modern scientific investigations. Recent projects in CA have already demonstrated the effectiveness of multi-purpose projects that include the development or strengthening of climate resilient farming, improving overall market accessibility, and building connections with available micro-finance schemes (e.g., MIAD project 2017).

The sharing of weather data for scientific purposes is also a major step to be taken mainly by the national hydro-meteorological agencies of Tajikistan and Kyrgyzstan as the official authorities in the two countries. Some capacity building initiatives that have been taken between research institutes and the two agencies for the upgrading of software systems and information exchange are still in an incipient stage (Alford et al. 2015).

Concluding remarks

Mountain societies of developing countries are subject to higher economic and climate vulnerability than societies in lowland and other regions. The degree of climate vulnerability of rural communities in the Pamir and Tien Shan mountains is yet hard to comprehend due to data and knowledge constraints concerning the environmental and socio-ecological context. The microclimate of glaciated zones of Pamir and Tien Shan and the effects of ice and snow melting on the hydrological cycles of major river basins, for instance, are still poorly understood. The contribution of pre-existing social deprivation to overall vulnerability and its linkages with climatic drivers are yet unclear and require further research. The effects of the scientific and infrastructural vacuum created after the end of the Soviet-era are still underestimated. Adaptation strategies to improve the vulnerability status of mountain societies need to be carefully designed based on a sound scientific foundation and policy-evidence results in close engagement with local communities.

The current study wants to draw attention to a region which is still comparatively unknown in terms of its vulnerability to climate change as well as in terms of the adaptive capacity of its people. The effects of the predominantly dry climate of CA will in future be further exacerbated by climate change, especially in the form of increasing temperatures. Water resources and water management are of central importance in a region where a large part of the population still relies on heavily irrigated agriculture and pastoralism. This brings the mountainous area of CA into focus, which is home to the headwaters of an extensive river network which encompasses the entire region.

People inhabiting these mountains—mountain societies—are vulnerable to the effects of climate change but also to other manifestations of global change such as economic downturns and political instability. The vulnerability of mountain societies of CA is due to factors such as a poor accessibility, rough terrain, mountain-specific hazards, and scant resources which also affect rural communities worldwide. However, what makes their case unique is the recent history of this region, i.e., the collapse of the Soviet Union in the 1990s which has led to a general decline in infrastructure, services, and livelihoods and for some time even to a reversal of development trends. Understanding vulnerability to climate change in CA with its recent history of institutional collapse and re-organization requires also an understanding of other factors contributing to vulnerability, more perhaps than in other parts of the world.

Improving the adaptive capacity of mountain societies to climate change and related hazards faces similar challenges. The breaking-up of the region into several nations which do not yet place regional integration as highest priority is one cause, among others, for a hitherto fragmented approach to climate change adaptation. There are some encouraging developments in the area of policy formulation and implementation of adaptation activities that should be replicated on a larger scale. However, the harmonization of ongoing initiatives with governmental and non-government institutions, international organizations, academia, and civil society is a challenge to be faced in mountainous CA and the entire region at large. The current study is an attempt to identify the major research areas where climate adaptive capacity initiatives should concentrate for improving the livelihoods of mountain societies in the CA region.

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