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Managing Disaster Risks and Water under Climate Change in Central Asia and the Caucasus

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State of the art of knowledge on water resources and natural hazards under climate change in Central Asia and the South Caucasus

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1. Background / Scope

Climate change is expected to have profound impacts on water resources and natural hazards in Central Asia (CA) and South Caucasus (SC). Such impacts are critical to understand particularly in the context of rapid socioeconomic change which will have implications for vulnerabilities of populations in the region. This paper aims to provide a synthesis of the scientific evidence of these changes, their magnitudes and expected consequences for the South Caucasus and Central Asia. These are two distinct regions, which climatically can be divided roughly as North Central Asia (CAN), South Central Asia and East Caucasus (CAS), High Central Asia (CAH) and western Caucasus (CCW).

The paper starts from an analysis of observed and projected changes in term of the atmospheric drivers of change, e.g. air temperature (TA) and precipitation (PR) anomalies at the global and regional level. Observed climate change refers to measurements taken at individual stations, satellite data and data obtained from assimilated meteorological data (re-analysis data). Climate projections are obtained by using quantitative methods to simulate the response of the main earth's system components (air, land, oceans, cryosphere) to an increase in greenhouse gas (GHGs) concentrations. Climate scenarios to simulate future GHG concentrations are given by the Representative Concentration Pathways (RCPs). In this paper we will refer to results for the RCP2.6 and RCP8.5 scenarios. RCP2.6 represents a mitigation scenario aiming at keeping the level of global mean temperature increase to 2°C above pre-industrial level, whereas RCP8.5 represents a scenario of business as usual with expected average temperature increase to 4°C above pre-industrial level. We then move to assess the state of knowledge on climate change impacts on water resources, weather extremes and mass movements. We discuss implications of climate change for the management of water resources and natural hazards through a risk perspective. We synthesize knowledge from peer review literature and to a certain extent key literature of international organisations. We have used available datasets to generate new graphs on climate and glacier changes in the region. The reviewed literature is necessarily biased towards Central Asia due to considerably less literature being available for the South Caucasus region.

2. Regional profiles

Central Asia consists of the ex-soviet republics of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan. Central Asia covers an area of 4 mi square kilometres and has a population of 60m people and a population density of just 15 people/km^2. It has a varied topography characterised by vast deserts, grassy steppes and high mountain ranges. Mountains cover approximately 20% of the area, with Tajikistan and Kyrgyzstan being the most mountainous countries (>90% of their territories). Major mountain ranges are the Tien Shan and the Pamir-Alai. The Tien Shan mountain range spans from Uzbekistan to Kyrgyzstan and in the southeast from Kazakhstan to China (Xinjiang). The West and North Tien Shan exhibit a relative moist climate whereas the eastern and inner ranges have a more marked continental climate. The Pamir mountain range is located in the South, mostly lying in Tajikistan. It hosts high mountain glaciers in its most arid areas. On the eastern side of the Pamir the climate is cold and arid whereas in the western and central side it is considerably wetter. Seasonal mean air temperatures from the observational dataset CRU[1] for the period 1981-2000 are in the order of 19°C in summer (JJA) and -7°C in winter (DJF) (Ozturk et al. 2017). Major river systems of the region include the Amu Darya and the Syr Darya. Major water bodies are the Aral Sea, Lake Balkhash and Issyk Kul, which are both part of the west/central Asia endorheic basin that also includes the Caspian Sea.

South Caucasus consists of the ex-soviet states of Armenia, Azerbaijan and Georgia and sits between the Black Sea (west) and Caspian Sea (east). The Caucasus has an area of 186,100 km^2 and a population of 16m people. The Caucasus mountains, which divide Europe from Asia, greatly influence the climate of the region. The region shows a marked topography within a very narrow distance. The highest point is Mount Shkhara at 5201m asl and the lowest point being -28m asl. The climate is extremely diverse varying with both longitude and altitude. The Great Caucasus range protects the region from the direct penetration of cold air masses from the north and strongly dictates the PR rates. PR decreases from west to east and generally mountain areas receive more PR than low-lying areas. The region shows an extreme PR gradient west to east with 2393 mm/year in Batumi (humid subtropical) and 258 mm/year in Baku (cold semi-arid), while mean annual TAs are quite similar at 14.2°C and 15.1°C, respectively. Largest rivers are the Mtkvari, the Kura and the Araks, with lengths of 1,564, 1,515 and 1,072 kilometres, respectively.

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[1] http://www.cru.uea.ac.uk/data

3. State of knowledge

3.1. Observed climate change

Mean annual TA has increased over the past century over most of the SC and CA region. The numbers of cold days and nights have decreased and the numbers of warm days and nights have increased across most of Asia since about 1950, and heat wave frequency has increased since the middle of the 20th century in large parts of Asia (Hijioka et al. 2014).

In line with observed northern hemisphere warming, large trends (>2°C per 50 years) in the second half of the 20th century were observed in the northern Asian sector (Hijioka et al. 2014). Most studies on CAH also document mean-annual (Hijioka et al. 2014) and summertime (e.g., Shahgedanova et al., 2010) warming, with slight cooling in the central and eastern Pamir (Aizen, 2011b), which is shown in Figure 1B. Although, the warming trend in mean annual TAs appears to be less pronounced at high altitudes than in the lower elevation plains and protected intramontane valleys (Unger-Shayesteh et al. 2013). However, for the winter months, a stronger warming trend can be detected at higher elevations of the Tien Shan Mountains (Kriegel et al. 2013; Mannig et al. 2013; Zhang et al. 2009).

PR trends, including extremes, are characterized by strong variability, with both increasing and decreasing trends observed in different parts of the region. In CCW, CAS, a weak but non-significant downward trend in mean PR was observed in recent decades, although with an increase in intense weather events (IPCC AR5 , Figure 1B). In CAH, PR increases have been observed more often than decreases (e.g., Braun et al., 2009; Glazyrin and Tadzhibaeva, 2011).

ERA-Interim[2] reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) shows widespread warming across the region (Figure 1B). Localised coolings are seen in locations such as the Pamir (in agreement with Aizen, 2011). PR anomalies show in general drying trends in the west of the region around the Caspian Sea and Caucasus but also in western China. Very localised wet anomalies can be seen in north-east Kazakhstan (in agreement with projected changes).

3.2. Projected climate change

The latest IPCC report[3] has shown that expected changes in TA (relative to normal period 1986–2005 and scenario RCP4.5) are quite consistent at 2-3°C across the region with the exception of CAN where winter warming is expected to be higher at 3-4°C, in agreement with the warming signal of high latitude regions. The Pamir region is also expected to see a higher rate of warming in summer of 3-4°C. Warming across the CA land area is projected to be higher than the global mean. The multi-model mean[4] summer warming in 2071–2099 is about 2.5/ 6.5°C above 1951–1980, in 2/ 4°C world, respectively (Reyer et al 2017, Figure 1). In line with the broad IPCC findings, results from the ISIMIP[5] project (Figure 1 below) show widespread warming of 2-3°C in RCP2.6, with a latitudinal trend. In RCP8.5 warming is much more intense at 6-8°C and additional warming hotspots over the high altitude regions of the Pamir and Southern Tian Shan.

Projected future changes in annual PR exhibit a southwest-northeast dipole pattern, with regions in the southwest becoming drier and regions in the northeast becoming wetter (Figure 1D). The "dry-getting-drier and wet getting-wetter" under climate change is a good first order approximation for the region. Wetting of the northeast is the most pronounced signal, in agreement with the strong global PR increases projected for high latitude regions in winters. The increase/decrease in PR is far more pronounced during the winter (DJF) than during summer (JJA) (Mannig et al.2013). The multi-model mean drying signal in the southwest, including the Caucasus region, is very weak (almost flat) under low-emissions scenarios (2°C world), and the models disagree about the direction of change. However, there is robust model agreement that under the high-emissions scenario (4°C world) the Caucasus region, Turkmenistan and Uzbekistan will receive less rain, with the multi-model mean annual PR dropping by about 20 percent.

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[2] https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era-interim

[3] WG1AR5: Annex I: Atlas of Global and Regional Climate Projections (http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_AnnexI_FINAL.pdf)

[4] Results from multiple models are averaged to account for uncertainties related to different modelling schemes.

[5] Acommunity driven modeling effort to provide cross-sectoral impacts of climate change based on the RCP scenarios www.isimip.org.

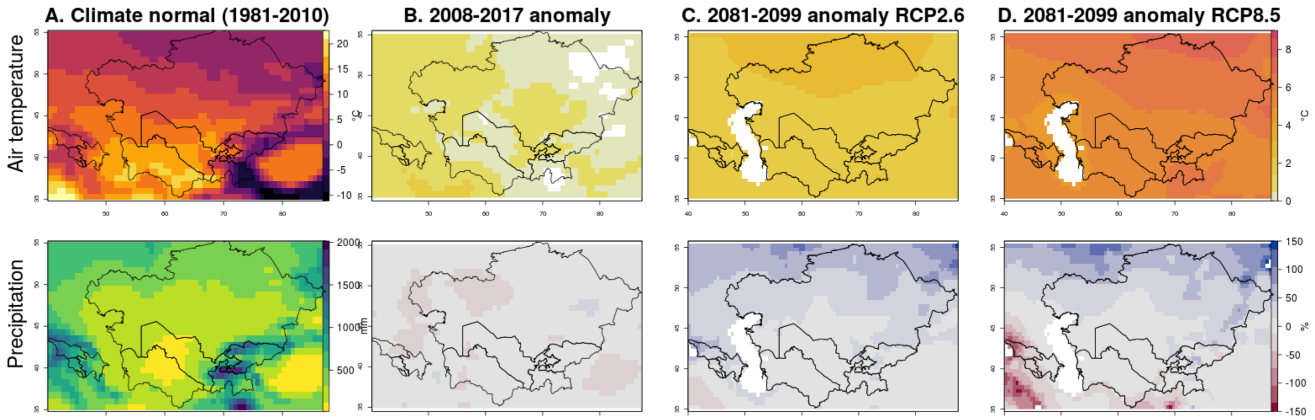

Figure 1: Observed and projected climate change in Caucasus and Central Asia as reported by ERA-Interim reanalysis for climate normals[6] (A) and current anomaly (B) and GCM multimodal means (Hempel et al. 2013) for RCP2.6 (C) and RCP8.5 (D) (projected changes 2081-2099). Cooling of up to 1 °C is shown in white in panel (B). Note all temperature scales are in °C; precipitation normal is in mm whereas precipitation anomalies are in % change.

3.3. Changing water towers

High mountain areas of the world are often referred to as "water towers" due to their critical role in supplying lowland regions with water supply. This is especially true for the large irrigated regions of both central Asia and Caucasus. Here, seasonal storage of freshwater as snow and inter-annual storage as glacier ice, provides a critical water reserve that permits agriculture and domestic water supplies during summer dry seasons as well as replenishing groundwater reserves. Therefore projected changes in high mountain water resources are critical to understand particularly in the regions that have seasonal PR regimes (Southern central Asia).

Glaciers: There is clear evidence from observations that glaciers are retreating throughout Central Asia (WGMS, 2018) and the Caucasus (WGMS 2018, Tielzide, 2016, Bondyrev et al. 2015, Shahgedanova et al. 2005) as a response to rising global TAs (Figure 2 below). Where multiple surveys are available, most show accelerating loss. Rates between –0.05% yr^{-1} and –0.76% yr^{-1} have been reported in the Altai (Surazakov et al., 2007; Shahgedanova et al., 2010) and Tien Shan (Lettenmaier et al., 2009; Sorg et al., 2012), and between –0.13% yr^{-1} and–0.30% yr^{-1} in the Pamir (Konovalov and Desinov, 2007, Aizen, 2011). Tielzide (2016) found that the area of Georgian glaciers reduced by 42.0 ± 2.0 % between 1911 and 2014, with highest retreat rate seen in the eastern region (67.3 ± 2.0 %). These ranges reflect varying sub-regional distributions of glacier size (smaller glaciers shrink faster) and debris cover (which slows shrinkage), but also varying proportions of ice at high altitudes, where as yet warming has produced little increase in melt (Narama et al., 2010). Marzeion et al. (2012) found 21st-century volume losses could be 50% for RCP2.6, and 67% for RCP8.5. The concept of peak water (Huss and Hock 2018 and references therein) is important to understand for glacial contributions to surface runoff. As melt rates increase, runoff will also increase until a certain tipping point that the glacial mass is reduced to such an extent that runoff starts to decline. The study of Huss and Hock (2018) found that for the basins of the Aral Sea this point is approximately mid-century. For the Caucasus this point is now and glacial discharge is likely decreasing over widespread areas. More immediately, glacial retreat creates a hazard due to the formation of moraine-dammed glacial lakes with possibility of outburst floods (GLOFs) (Bolch et al., 2011).

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[6] Climate is commonly described using the long-term averages of meteorological parameters (such as temperature, precipitation and hours of sunshine), as well as the differences from these averages. The 30-year average and 30-year averaging period are used as standard for climate normals worldwide.

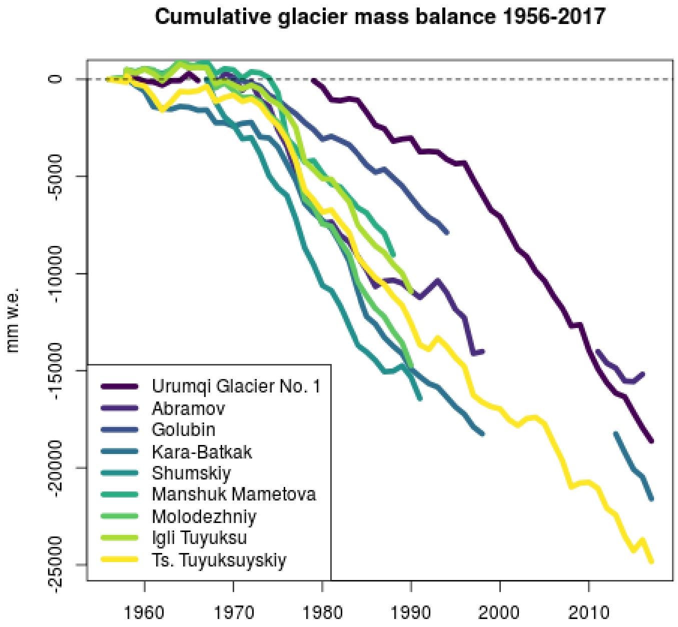

Figure 2: Changes in mass balance of central Asian glaciers over the past half century (credit: WGMS).

Seasonal snow cover: Over large parts of southern Central Asia seasonal snow cover contributes significantly to the annual water budget as PR is seasonal and falls mainly during autumn to spring, largely as snow in mountain regions. Observed warming in mountains of Central Asia and Caucasus is expected to be accompanied by reduction in seasonal snow cover as a higher proportion of winter PR falls as rain (Lemke et al. 2007). Zhou et al (2017) found significant decreases in number of snow on ground days throughout the Pamir and Tien Shan in an analysis of trends from 1986-2008. Global projections estimate an increase in the snow line of around 150 m per 1°C warming (Christensen et al. 2007). Expected changes in seasonality of snow melt will result in earlier runoff and reduced water availability in summer/late summer (Barnett et al. 2005) where demand in the large irrigated zones of Central Asia is highest, particularly in unregulated catchments. Changes in seasonal snow cover are projected to enhance warming in mountain regions through snow-albedo effects (Christensen et al. 2007). In the Amu Darya basin studies have found that increasing glacial runoff will buffer decreasing snowpacks until mid-century when peak water is expected in many areas (Huss & Hock 2017, Figure 3). However, the second half of the century will then see decreasing runoff as both snow and glacial components decrease.

3.4. Extreme weather events

The effects of climate change are projected to cause shifts in present day climate into new regimes, where what we consider to be extreme events today will be increasingly common in the future.

Heat Extremes: Reyer et al. (2017) found that threshold exceeding heat extremes strongly increase in southern regions in a 4 °C world with respect to the reference period 1951-1980. Heat extremes can be quantified as 3- and 5-sigma events (considering that monthly temperatures are close to a normal distribution, 3- and 5-sigma events represents 3 and 5 standard deviations over the mean temperature, respectively). In a region from Eastern Caucasus to Central China they found 80% of summer months to exceed 3-sigma and 40% 5-sigma events. To put this into context, TAs experienced during the warmest 10 percent of summer nights during the 1961–1990 period are expected to occur in about 30 percent (2˚C world) or 90 percent (4˚C world) of summer nights by the end of the century in regions approximately below 50° latitude (Sillmann et al. 2013). This will likely increase heat stress considerably in human populations, livestock and agricultural crops as well as enhance drought impacts.

Precipitation Extremes: No clear trend in PR extremes can be found in the observation record (Dai 2013, Donat et al. 2013); however a moderate drought risk is projected until the end of the century with 10% decrease in soil moisture in CAS and Caucasus. Although Sillmann et al. (2013) found no significant change in the index “consecutive drought days” in their study Central Asia model domain (includes Caucasus). Changes in soil moisture in CAN are likely to be slightly positive. However, warming will have a large influence on soil moisture due to enhanced evapotranspiration. Reyer et al. (2017) found significant increases in land area classified as both arid (19.6, 11.6) and hyper arid (22.4, 14.4) in both 2 and 4 °C worlds, respectively. Specifically, under a 4°C world significant increases in aridity in already drought prone regions such as southern Kazakhstan, Uzbekistan, and Turkmenistan can be expected, with serious implications for agriculture and food security. Although drought projections remain uncertain, at least in the PR signal, regional water availability will be strongly affected by changes in river runoff due to glacier melting and changes in seasonal snow storage (next section). Atmospheric warming speeds up the hydrological cycle and is expected to increase the frequency of intense PR events throughout the region (Sillmann et al. 2013). Mountainous regions of central Asia are very prone to flash-flooding which can occur after intense PR events particularly in steep rocky catchments with narrow canyon outlets. There are many well-documented cases of entire villages being destroyed by this type of events such as the seven-lakes event in 1992 in the Fan mountains, Tajikistan.

3.5. Mass movements

Mass movements are complex phenomena with possible climate triggers e.g. glacier lake outburst floods, debris flows, rock fall and ice/snow avalanches. In general warming in high mountain regions can lead to destabilisation of steep slopes due to loss of mechanical strength e.g. permafrost debris/rock slopes. While climate induced permafrost degradation (observed at GTNP[7] sites in Tien Shan e.g. Marchenko et al., 2007) can be a key driver of such events, it is not straightforward to disentangle the climate signal from normal mass wasting processes in mountain areas. However there is increasing evidence that increased incidence of thermally induced slope instabilities should be expected as high mountain regions warm. A second class of more mechanical mass-wasting is debutressing due to glacial retreat that leaves oversteeped slopes eroded by the former glacier flow. These slopes are inherently unstable and prone to collapse. Snow avalanches are significant hazards in both central Asia and Caucasus and can threaten exposed infrastructure and settlements. Impact of climate change on snow avalanches is complex and uncertain. Reduced average snowpack depths would serve to reduce frequency of large events. Although there is some evidence of large PR events in winter becoming more frequent which would promote large avalanche events even with a background of lower average snow depths. Mass movements often result in compound events which can impact distant low lying regions (Mergelli et al. 2018). Compound events are usually associated with different interacting physical processes over multiple temporal and spatial scales (Zscheischler et al. 2018), e.g. a glacier lake outburst flood triggered by an impact wave from an ice avalanche upstream, which in turn triggers a debris flow with entrainment of material. Earthquakes can often be the trigger of such compound processes and while not coupled to climate can trigger mass movements on slopes destabilised by warming.

Box 1: Compound events on Mount Kazbek Massif, Caucasus

On May 17, 2014 an ice avalanche released from the Devdoraki Glacier on Mt. Kazbek (5033m) in Georgia. The ice avalanche triggered a massive mud and debris flow. The flow travelled downstream to the Tergi River, which was temporarily blocked and gave rise to a 20-30 m deep lake with a water volume of 150'000 m3. The debris covered a highway of international importance between Georgia and Russia, the international gas pipeline and the building site of a new hydropower plant were damaged. The disaster claimed the lives of nine people and created disruption in the downstream communities (Tielidze 2017). This is the same region from which in September 2002 ice and rock from a hanging glacier released onto the Kolka glacier triggering a massive avalanche of ice, snow and rocks into the Valley river. The avalanche swallowed the village below and several other settlements.

Ice avalanche release zone, Mt Kazbek, May 2017. Source: Geopraevent

4. Knowledge gaps and uncertainties

4.1. Models

Climate projections simulate the response of the climate system to a scenario of future greenhouse gas emissions and are derived using climate models. Climate models can be understood as numerical representations of the climate system based on biological, chemical and physical properties of the atmosphere, cryosphere, land and ocean components including their interactions and feedbacks. The most advanced climate models are General Circulation Models (GCMs), with a spatial resolution of 100-300 km, as used by the IPCC and literature in this review to assess climate change at global scales. Coarse resolution means that topographic features even as large as the Pamir Tien Shan are not well resolved and therefore surface processes are not well represented leading to generally greater uncertainties in mountain regions as compared to low lying regions. Our projections may also be informed by observations in the case of debiasing which again is problematic in mountain regions where observations are sparse and not representative of larger regions. Regional Climate Models can address the resolution problem to some extent by downscaling but are still prone to uncertainties related to surface process representation.

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[7] Global Terrestial Network for Permafrost mandated by Global Climate Observing System/WMO

4.2. Observations and networks

Glacier, snow and permafrost in situ measurements and monitoring constitute the data basis for ascertain changes and process understanding in upstream and downstream systems due to climate change. Thus, long term and continuous in situ observations and measurements are of paramount importance to address climate change impacts on water resources and natural hazards. Continuous in situ measurements and monitoring in remote areas such as the mountain areas of Central Asia and the Caucasus are challenging tasks due to the difficult access, complex topography, financial and logistic constraints, political instability as well as lack of appropriate infrastructures (Hoelzle et al. 2017). Several studies have reported the lack of appropriate and reliable data sets as one of the most important constraint to understand patterns of changes in Central Asia (Unger-Shayesteh et al. 2013, Hoelzle et al. 2017). Most areas of the Asian region lack sufficient observational records to draw conclusions about trends in annual PR over the past century (Hijioka et al. 2013; Figure 24-2; Table SM24-2). If weather stations are present at all, they are usually located at lower elevations where most of the population lives. There are very few datasets above 3000 msl and virtually none above 5000 msl. Remote sensing data as well as model-assimilated observations (from reanalysis data) are used to fill the observational gap. Their products are becoming increasingly popular and show increased skills. However, the relatively short time series and coarse resolution do not allow for robust assessments of changes in mountain areas, where the complex topography requires finer enough resolutions (< 5 km) (Prein et al. 2015). This makes the case for denser observational networks in remote mountain areas ever more urgent.

Management of extreme events and mass movements requires monitoring, recording and reporting of events over relatively long time scales and standardised data reporting. In locations where resources are scarce and funds are limited, this is often not a priority. Permafrost monitoring is also very important for understanding slope stability and the influence of permafrost on water resources. Permafrost monitoring is patchy in the regions which account for only 5 permafrost boreholes in Central Asia (all with discontinuous measurements) and none in the Caucasus (Biskaborn et al. 2015).

First steps have been undertaken to re-establish monitoring sites and to build capacities and innovations through international projects such as the Central Asia Water (CaWA[8]), an international consortium of German and Central Asia institutions, the Capacity Building and Twinning Climate Observing System of the Swiss Agency for Development and Cooperation (CATCOS[9]), the Water Management in the South Caucasus of the USAID and the Central Asia Hydrometeorology Modernization Project (CAHMP[10]) of the World Bank.

5. Implications for water and disaster risk management

The IPCC risk framework in the background of Figure 3 (IPCC 2012, 2014) provides a useful approach to discern the different drivers of climate risks for a country or a region. It recognises that climate impacts and risks are given by the complex interplay of multiple factors, not least the past and current pathways of socio-economic and political development. This perspective is useful for addressing current and future management issues since it distinguishes the physical causes of risks (hazards as discussed in the previous section) from causes related to exposure (number of people, infrastructures) and past and present pathways of development (vulnerability) (Allen et al. 2018). In this section we look at the risks associated with changes in water resources and changes in the natural disaster landscape as a consequence of climate change and highlight the exposure and vulnerability contributions to climate related risks (Figure 3).

Due to the semi-arid to arid climate, Central Asia and part of South Caucasus are heavily dependent on fresh water supplies from snow and glacier melt for irrigation, hydropower and domestic use. Changes in timing (seasonality) and amounts of fresh water can have serious implications for the future management of irrigated agriculture and energy generation from hydropower supplies. The effect will be most strongly felt in the large irrigation zones of central Asia such as Samarkand and Bukhara, but also in upstream hydroelectric potential of schemes such as the Nurek dam in Tajikistan. Mankin et al. (2015) conducted a global study of sensitivity of individual basins to changes in snow supply under climate change projections. They found that currently the basins of CA significantly depend on snowmelt to serve summer demand (demand refers to surface and subsurface water consumption from agricultural, industrial and domestic use), whereas in the Caucasus rainfall is sufficient to meet demand. In addition, they found a high risk that snow melt will no longer meet summer demand by mid-century in central Asian basins. They also found evidence for a shift from sufficient to insufficient rainfall runoff to meet water demand in the Caucasus region by 2080. Given the already very high level of water stress in many parts of Central Asia, observed and projected TA increases and PR decreases in the western part of Kazakhstan, Uzbekistan, and Turkmenistan (cf. Figure 1) could exacerbate the problems of water shortage and distribution (Lioubimtseva and Henebry, 2009). Considering

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[8] http://cawater-info.net/

[9] https://www.meteoschweiz.admin.ch/home/forschung-und-zusammenarbeit/projekte.subpage.html/de/data/projects/2011/catcos.html

[10] http://projects.worldbank.org/P120788/central-asia-hydrometeorology-modernization-project?lang=en

the dependence of Uzbekistan's economy on its irrigated agriculture, which consumes more than 90% of the available water resources of the Amu Darya basin, climate change impacts on river flows would also strongly affect the economy (Schlüter et al., 2010).

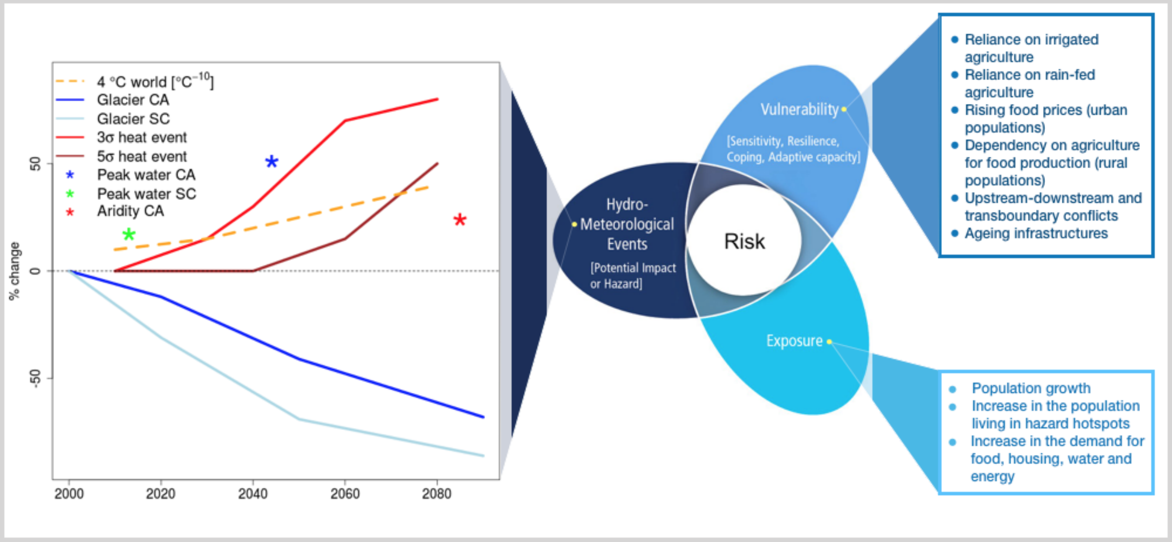

Figure 3: The risk concept adapted from the IPCC (2012, 2014), which highlights the interactions between hazard, exposure and vulnerability as components of risk. The hazard box (left end side) synthesizes the main trends from current observations and projections until the second half of the century as reported in this paper. The right end side summarises main elements of current vulnerability and exposure common to both regions as collected from the reviewed literature.

Recent studies have demonstrated that the risk of water scarcity in the region is strongly associated with high water demand driven by socio-economic pressure and increasing demographic trends (increased exposure) (Luck et al. 2015). In Central Asia, inefficient water usage for irrigation and degradation of croplands has already resulted in 30% fall in crop productivity since the 1990s (Conrad et al. 2013). Depending on the climate scenarios, agriculture productivity might decline by as much as 20%-50% by 2050 (compared to 2000-2009 baseline) in Uzbekistan and up to 30% in part of Tajikistan if appropriate adaptation measures are not implemented (Reyers et al. 2017). Loss of agricultural productivity combined with soaring population and food prices can have direct impacts on food security for large sections of the population. In the already water stressed and drought prone areas of the Ararat valley in Armenia, climate change is expected to lead to enhanced TA and reduced PR resulting in more frequent drought conditions. Furthermore, an expected reduction in the flow of the major river (Arpy River) and a decrease in groundwater levels will pose serious challenge for a country dependent on agriculture for more than 20% of its GDP (Melkonyan 2015). In parts of Azerbaijan existing water stress due to inefficient use, unequal distribution and seasonal fluctuations are causing already major concerns. Improved water use efficiency in irrigation, changing/rotating crop systems and water reuse might ease water stress and improve agriculture productivity (Aleksandrova et al. 2014).

The presence of a marked downstream-upstream topography renders the two regions particularly prone to gravitational hazards such as landslides, debris flows, mud flows, ice/snow/rock avalanches and GLOFs. While it is still statistically difficult to directly link such events and frequency of occurrence to shifts in global climate there is growing evidence from the Alps (Huggel et al. 2012) and a sound physical basis for increased occurrence of mass movements in high mountain regions. As permafrost slopes warm they become less stable, as glaciers recede they leave behind inherently unstable slopes that have been 'oversteepened' due to erosive glacial flow as well as large amounts of sediments that can be mobilised in large destructive debris flows.

However, the sequence of processes leading to these type of hazards needs to be reasonably well understood to devise appropriate adaptation and disaster risk reduction strategies. Several other contributing effects or confounders play a role in the dynamics of disasters generated by gravitational hazards, such as the increased number of people and assets in hotspot areas (exposure) as well as lack of appropriate risk preparedness and information (vulnerability). It is thus of paramount importance to intensify the development of soft adaptation measures which are flexible, robust and non-regrets and that allow for adaptive management (Hallegatte 2009), hazard, exposure and vulnerability mapping, capacity building and training, Early Warning Systems (EWS).

Box 2: Transboundary processes and management challenges

The Syr Darya river basin originates from the Tian Shan Mountains in Kyrgyzstan, briefly flows across Tajikistan, Uzbekistan and Kazakhstan to end in the Aral Sea. During the soviet era extensive irrigation in the downstream countries of Uzbekistan and Kazakhstan was developed. Upstream countries provided water for spring and summer irrigation to the downstream countries and received fossil fuels in exchange. After the breakdown of the Soviet Union, Kyrgyzstan, which is poor in fossil fuels, started storing water in spring and summer to be used in the fall and winter for hydropower generation. The downstream countries, however, still need large amount of water during April-September for irrigation. Projections show that for the Aral Sea Basin peak water could be reached in 2030±5 (RCP2.6) and 2044±15 (RCP8.5) followed by a steady decline in glacier run off (Huss & Hock 2018). The impacts of glacier melting and reduced snow cover will be felt both upstream and downstream. Additionally, studies on cooperation regimes indicate that Central Asia has a moderate to high risk of conflicts due to reduced water availability (Bocchiola et al. 2017). The major challenge for the region is thus to manage the diverging needs of the upstream and downstream countries through appropriate transboundary cooperation. To facilitate transboundary cooperation, dynamics of water flows and management need to be well understood to devise appropriate adaptation solutions for the region (Bocchiola et al. 2017).

6. Key messages

- Climate change is well underway in both regions, positive TA anomalies are observed throughout both regions and drying trends seen in the western regions of Central Asia and Caucasus. Warming is projected to continue throughout the region and depending on scenario ranges from a “manageable” 2-3 °C to a dangerous 5-8 °C. Particular hotspots of TA increase are Northern regions of Kazakhstan and Pamirs/ South Tian Shan.
- Drying trends are likely in South western parts of Uzbekistan and Turkmenistan and Caucasus, increasing risk of more frequent and longer periods of drought.
- Caucasus will likely no longer rely on sufficient rainfall to meet summer demand by late century with increased dependence on depleted snow/glacier melt water resources.
- Significant increases in heat stress in human populations, livestock and crops is very likely throughout both regions during summer months.
- Glaciers are retreating in both regions and will continue to retreat over this century. Peak water has likely already been reached in the Caucasus and will be reached by mid-century in Central Asia. Glacial water resources will decrease after this tipping point. The risk of Glacial lake outburst flood is expected to increase.
- Decreasing PR, increasing evapotranspiration and reduced runoff from snow and glacial melt will likely combine to severely reduce water resources particularly in irrigated zones of central Asia in the second half of this century.
- Permafrost mountain slopes throughout both regions will experience thawing during this century over wide areas increasing the chance of mass movement events such as rockfall, ice avalanches and debris flows. These high mountain events can often travel large distance and effect low lying communities through complex process chains.
- Lack of adequate monitoring of key environmental variable is a key limitation in understanding past and future trends. Investment in monitoring networks also requires capacity in data management and interpretation as well as maintenance of systems.
- Climate change risks need to be assessed within the specific exposure and vulnerability context of the region in order to devise appropriate adaptation solutions for water and disaster management.

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