Report

Managing climate risks to protect net-zero energy goals

Net-zero transition opportunities in Kyrgyzstan, Tajikistan and Uzbekistan

Sarah Opitz-Stapleton, Olena Borodyna, Ilayda Nijhar, Vikrant Panwar and Rebecca Nadin, with Farukh Kasimov, Sardor Koshnazarov and Azamat Usubaliev

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About the authors

Sarah Opitz-Stapleton

Research Associate with ODI's Global Risks and Resilience programme. A climate scientist and hydrologist by training, she works at the intersection of climate services and systemic disaster risk management, including climate adaptation and low-carbon transition. Her interests include working with governments to better understand interconnected, cascading and transboundary climate, environmental and geopolitical risks, and how to manage these to protect investments. ORCID: https://orcid.org/0000-0002-4710-6692

Olena Borodyna

Senior Transition Risk Analyst with ODI's Global Risks and Resilience programme. A geopolitical risk analyst by training, she has worked with think tanks and in the corporate sector. Her interests span the risks and opportunities of geopolitical and low-carbon transition, social and political risk management of investments in emerging economies and China's geostrategy.

Ilayda Nijhar

Global Risk Analyst with ODI's Global Risks and Resilience programme. A political risk analyst by training, she focuses on geopolitical trends and implications for the energy sectors in the Caspian and Central Asia regions.

Vikrant Panwar

Senior Researcher with ODI's Global Risks and Resilience programme. An economist specialising in macro-fiscal disaster impacts, he conducts research around fiscal climate and disaster impacts at the sovereign and sub-sovereign levels.

Rebecca Nadin

Director of ODI's Global Risks and Resilience programme and the Head of ODI's Global China 2049 initiative. She manages a team of policy analysts and experts exploring the risks emerging from intersecting global challenges such as climate change, transnational crime and geopolitical volatility.

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Acronyms

ADB	Asian Development Bank
APHRODITE	Asian Precipitation – Highly-Resolved Observational Data Integration Towards Evaluation
CASA-1000	Central Asia–South Asia Power Transmission and Trade Project
CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Downscaling Experiment
GCM	General Circulation Model
HPP	hydropower plant
IPCC	Intergovernmental Panel on Climate Change
PV	photovoltaic
RCM	Regional Climate Model
RCP	representative concentration pathway
T_{max}	daily maximum temperatures
T_{min}	daily minimum temperatures
TPP	thermal power plant
UNDP	United Nations Development Programme

Executive summary

This study is a preliminary risk screening of regional climate change risks to electricity generation, transmission and distribution infrastructure in the Kyrgyz Republic, Tajikistan and Uzbekistan. All three countries have established green energy visions and are pursuing renewables portfolios of small- to utility-scale solar, wind and hydropower projects through mixed financing from development banks, the Green Climate Fund and private investment.

While the expansion of renewables and transitions to net-zero carbon economies are necessary to avoid catastrophic climate change, such renewables infrastructure investments need to be resilient to a number of rapidly changing threats related to climate change, environmental degradation and cyber-attacks. Low-carbon energy systems also need to be able to meet the opportunities of diversifying economies and new technologies, such as widespread use of electric vehicles. Yet planning for the long time horizons of climate change is novel for many energy policy-makers and energy companies around the world. Energy infrastructure is a significant investment, with the expected lifetime of utility-scale solar ranging from 25 to 40 years, and hydropower plants around 80 years. A climate hazard may not only impact a specific piece of infrastructure but also trigger cascading impacts throughout the energy system, as well as ecosystems.

This study draws from analysis of projections from high-resolution regional climate models from the Coordinated Regional Downscaling Experiment (CORDEX), combined with a review of national climate and disaster risk management plans and literature around climate change risks to energy infrastructure to present the preliminary risk screening. CORDEX regional models belong to the suite of international climate models that informed the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment. However, they have not yet been incorporated into the national assessments of Kyrgyzstan, Tajikistan and Uzbekistan. Drawing on this set of models expands the suite of models for examining more localised climate risks to infrastructure.

Climate change impacts are already being felt across the three countries in this study. Clear and statistically significant increases in maximum and minimum temperatures across all three countries and at most elevations are detectable over the past few decades. CORDEX projections for the 2050s (2036–2065) indicate potential increases in mean annual maximum temperatures of between 1.8°C and 2.2°C for most of the region under Representative Concentration Pathway (RCP) 2.6 and RCP4.5, with increases of up to 4.0°C for the Pamir-Alay and eastern Pamirs in Tajikistan. Mean annual minimum temperature increases are also more pronounced over the Pamir, Pamir-Alay and parts of the Tian Shan – up to 3.1°C under RCP2.6 and 3.6°C under RCP4.5. By the 2050s, under RCP2.6, most of the Bukhara region and a swath extending from southern Navoi eastwards in Uzbekistan are projected to experience 60+ days with daily maximums exceeding 33°C between July and September; under RCP4.5, more than half of Uzbekistan faces heatwaves.

The spatial variation in the projected changes in precipitation is significant under RCP2.6 and RCP4.5, with some areas projected to experience increases, and others to face decreases. The intensity and frequency of daily extreme rainfall events are projected to increase, with what was once the 1-in-100-year 24-hour precipitation event becoming a 1-in-20-year event in some locations. Warming temperatures and potential precipitation shifts are already impacting glaciers and river discharges, and will continue to do so. Depending on the glacier's size, elevation and location in respect to higher/lower rates of warming, critical points might be reached in some catchments such that glaciers and snowpack may no longer be able to contribute much to river baseflows or peak flows. In the Big Naryn Basin, the critical point is expected in the 2040s; it has already been reached in the Small Naryn. This has implications for hydropower and management of energy systems.

New solar photovoltaic, wind and hydropower generation are being constructed or are planned as part of country net-zero energy ambitions. Regional transmission networks are also being strengthened, such as through the Central Asia–South Asia Power Transmission and Trade Project (CASA-1000). Infrastructure built now or before 2030 will have to contend with projected changes in the 2050s; hydropower and thermal power plants have longer lifetimes and must be prepared to handle the climate of 2100. Given regional interconnectedness, damage or disruption to generation or transmission at one point due to a climate hazard event can cascade risks throughout the regional power distribution system. There is the possibility of drought or heatwaves extending over a multi-country area, with cascading regional consequences for grids and the ability to meet demand.

New regional climate risk management policies and insurance facilities are needed. Resilience in the energy system requires anticipation of future risks and demand. Proactive risk management should deploy full semi-quantitative to quantitative climate change and disaster risk (including cybersecurity) assessments as part of environmental impact assessments for planned energy infrastructure in each country. While an infrastructure-specific assessment is required, it must be embedded within a basin or system-wide assessment. An individual generation or transmission infrastructure is part of the larger regional water-energy system; climate risks are transboundary. The following summarised recommendations offer starting points towards proactive risk management to protect net-zero energy investments, national economies and further economic development goals:

Recommendation 1: Update national disaster risk management policies and National Adaptation Plans to require all-hazards risk management for infrastructure, and develop a regional all-hazards risk management framework and guidelines.

Recommendation 2: Require semi-quantitative to quantitative all-hazards risk assessments for infrastructure, and develop a regional energy system assessment.

Recommendation 3: Continue to rehabilitate weather, river and glacier monitoring stations, and increase their numbers for better observational data. National hydrometeorology agencies should join CORDEX and other global climate modelling initiatives that underpin the IPCC Assessments.

Recommendation 4: Consider cost-effectiveness, robustness and co-benefits of potential energy infrastructure over the short and long term, with the costs of climate change and failure to adopt robust infrastructure factored in.

Recommendation 5: Increase diversification of generation types, and strengthen transmission and distribution grids, but consider where they are built, to reduce exposure and transmission losses.

Recommendation 6: Join the Asian Development Bank's CAREC Disaster Risk Transfer Facility to reduce financial risks while enhancing regional collaboration on climate and all-hazards risk management.

Recommendation 7: Continue to strengthen efficiency efforts to reduce energy and water demand, and use both within country and in coordination with regional partners.

1 Introduction

1.1 Overview

The Kyrgyz Republic, Tajikistan and Uzbekistan have ratified the Paris Agreement and are each in the process of updating and strengthening their Nationally Determined Contributions and National Adaptation Plans. Each country is also concerned with energy security and its implications for socioeconomic development. In keeping with commitments under the Paris Agreement, the three countries are starting to prioritise diversification of their electricity generation portfolios to renewables, as well as increasing energy efficiency. While these shifts are positive, much work remains to be done and focus applied to keep renewables and efficiency ambitions on track or even to consider increasing ambition.

Critical infrastructure, such as electricity generation, transmission and distribution lines and liquified natural gas pipelines, are exposed to a number of hazards and threats ranging from human-made (e.g. cyber-attacks and climate change) to natural (e.g. earthquakes and natural climate variability). When infrastructure is damaged or destroyed during a hazard event, impacts can quickly cascade and cause disruptions and socioeconomic losses across systems. For example, the 2012 Hurricane Sandy is estimated to have caused $60 billion in economic losses along the east coast of the United States, disrupting transportation lines and leaving 8.5 million households and businesses without electricity (OECD, 2019; Strauss et al., 2021).

Threats and risks to energy infrastructure are evolving rapidly. Climate change is altering not only the frequency and intensity of extreme events such as heatwaves and severe storms, but also average seasonal temperatures and precipitation (IPCC, 2022). The spatial variation of such climate shifts is not equal; some areas (and, as a result, infrastructure) will be more exposed than other areas or exposed to new threats not faced historically.

Technological advances also present risks and opportunities with implications for generation and transmission. Industrial development, urbanisation, population growth, bitcoin mining, transitions to electric vehicles and overall increasing standards of living are leading to increasing energy demands. Yet cyber-attacks are becoming more sophisticated and have the potential to disrupt grids and damage infrastructure, leaving millions of homes, businesses and hospitals without electricity, while causing knock-on impacts on other critical infrastructure such as water supply and wastewater treatment. It is also no longer inconceivable that one country might launch a cyber-attack against another's energy infrastructure at the same time as a drought or other climate-related hazard is occurring.

As existing energy infrastructure is retrofitted and upgraded, and new generation and transmission planned, the changing nature of hazards and risks needs to be considered. Just because hydropower on a particular river is currently promising does not mean that the potential will remain the same in 40 or so years, due to climate change-induced shifts in temperature and rainfall. A thermal power plant designed using historical precipitation and temperature data might not have the capacity to handle seasonal shifts and more intense extremes due to climate change. Each individual infrastructure has particular climate sensitivities

Box 1 Climate risk definition

‘The potential for adverse consequences for human and ecological systems … In the context of climate change, risks can arise from the potential impacts of climate change as well as human responses to climate change … Risks result from dynamic interactions between climate-related hazards with the exposure and vulnerability of the affected human or ecological system to the hazards.’

Risks to infrastructure result from the vulnerability (e.g. operational water requirements or demand loads during extreme heat events), exposure (e.g. a hydropower plant situated in a region with high glacier melt rates) and the climate change hazards to not only individual infrastructure but the energy system as a whole.

Source: Adapted from IPCC (2022) and Forzieri et al. (2015)

or thresholds at which negative impacts begin to accrue. But it is not just individual infrastructure but the whole energy system that needs to be considered, as risks are ‘built in’ and can cascade along country and regional energy systems. All-hazards risk management needs to be incorporated within the planning, design, construction, operation and maintenance phases to protect investments, reduce financial risks and ensure that needed energy exists to realise desired socioeconomic gains.

1.2 Preliminary risk screening

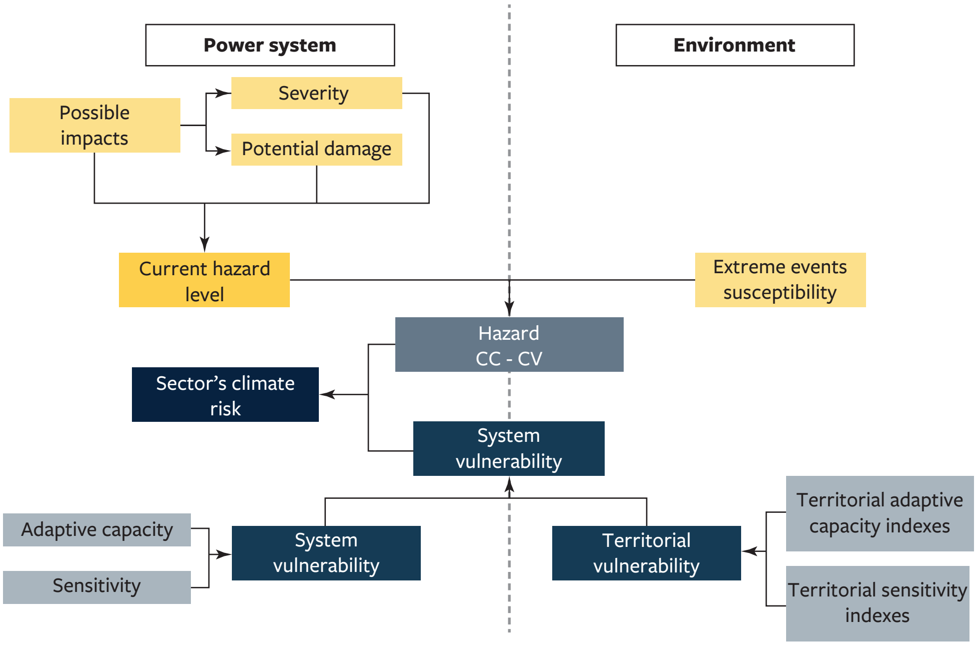
This project ‘Provision for enhanced evidence-based and ambitious climate policy in Central Asia’ demonstrates the socioeconomic and investment opportunities in transitioning to net-zero economies and provides a preliminary risk screening of the climate risks that need to be managed to protect renewable energy assets and investments under construction and prioritised by the three countries – hydropower, wind and solar.

Preliminary risk screenings allow for a rapid identification of: (1) climate change-related hazards to which both individual infrastructure and an energy system are exposed (spatial extent of hazards); (2) design, operational and human management vulnerabilities of infrastructure; and (3) the direct and cascading risks that could result (Willows and Connell, 2003; Sánchez-Sierra et al., 2021). Such a screening assists in qualitatively mapping out the direct impacts – damage, disruption or destruction – that could happen to generation, transmission or distribution infrastructure should a climate hazard occur, and how those impacts could cascade through energy systems and surrounding ecosystems (see Figure 1).

The report is laid out in the following structure, as a preliminary risk screening:

- Chapter 2 identifies scenarios of potentially significant shifts and extremes in temperature and precipitation due to climate change.
- Chapter 3 outlines which infrastructure might be exposed due to expected spatial distributions of such shifts and presents a preliminary risk screening drawing from the climate projection analysis and a review of secondary literature.

Figure 1 Energy system risk typology



Source: Sánchez-Sierra et al. (2021: 5)

- The report closes with a discussion of current good practice in climate risk management in energy infrastructure in Chapter 4.

We do not call it 'best practice', as there is still much to be learned. Climate change risk management in energy design, planning and operations as part of an all-hazards approach is still nascent. Panwar et al. (2022) outlines the opportunities of moving to net-zero carbon economies.

2 Scenarios: climate trends and 2050s projections

2.1 Methodological overview

Climate change projections must be compared against historical datasets from a baseline period. The Asian Precipitation – Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE) gridded daily precipitation data is the primary long-term (1951–2005) high-resolution dataset for Central Asia. APHRODITE precipitation data were compiled and interpolated from observation datasets shared through cooperative agreements with national hydrometeorological agencies and international organisations (Yatagai et al., 2012). By integrating multiple sources of observation data, APHRODITE overcomes the decrease in weather station density and gaps in records following the break-up of the Soviet Union. Such gaps in weather station data make station-scale downscaling and bias correction of future climate projections difficult.

For this reason and the need to examine changes across the three countries, we used APHRODITE rather than station data from the hydrometeorological agencies. A baseline historical period of 1971–2000 was used for precipitation data. High-resolution gridded daily maximum and minimum temperature data are derived from ERA-Interim data (Dee et al., 2011), and a baseline historical period of 1981–2005 was used. ERA-Interim data are used as the historical comparator dataset in the Coordinated Regional Climate Downscaling Experiment (CORDEX).

General Circulation Models (GCMs) are climate models used to explore how the climate might change. Under the latest set of model experiments, the sixth phase of the Coupled Model Intercomparison Project (CMIP6), which supported the IPCC Sixth Assessment, dozens of models were run by institutes around the world. GCMs simulate continental climates well, but their grid resolution of around 100–500 km is too coarse for projecting climate changes at local to regional levels or for use in climate risk and adaptation assessments.

Dynamic Regional Climate Models (RCMs) or statistical downscaling techniques must be used. For this study, we used daily temperature and precipitation projections from the CORDEX Central Asia domain. CORDEX is an international, cooperative climate modelling effort, through which multiple RCMs are driven by GCMs. CORDEX models also supported the IPCC Sixth Assessment. The grid resolution of the CORDEX projections over the study domain is 0.22° or 0.44°, or approximately 24–50 km. The RCM-GCM combinations and Representative Concentration Pathways (RCPs) we used for our analysis are shown in Table 1.

The projections of climate models should not be used directly when conducting risk modelling and assessments for infrastructure. These models have biases in how they simulate local, regional and global historical climates (Seneviratne et al., 2021), and these biases can carry forward in the future projections. Therefore, the climate science community uses a number of bias correction techniques to remove biases from future projections without removing the climate change signal. For this study, we used nonparametric quantile mapping. A more detailed explanation on methodology is provided in the annex.

Table 1 CORDEX models suite used in the study

RCP2.6	**GCM-RCM experiment**	**Description**
	NCC-NorESM1-M, GERICS-REMO2015_v1	Norwegian Climate Centre (NCC) – Earth System Model; Climate Service Center Germany Regional Model (REMO)
	MPI-ESM-MR, GERICS-REMO2015_v1	Max Plank Institute for Meteorology (MPI) – Earth System Model; Climate Service Center Germany Regional Model (REMO)
	MOHC-HadGEM2-ES, GERICS- REMO2015_v1	Met Office Hadley Centre (MOHC) – Hadley Centre Global Environment Model v2; Climate Service Center Germany Regional Model (REMO)
RCP4.5	**GCM-RCM experiment**	**Description**
	MOHC-HadGEM2-ES, RegCM4-3_v5	MOHC; The Abdus Salam International Center for Theoretical Physics (ICTP) Regional Climate Model (RegCM4)
	MPI-ESM-MR, RegCM4-3_v5	MPI; The Abdus Salam International Center for Theoretical Physics (ICTP) Regional Climate Model (RegCM4)

Source: CORDEX (2021)

This project focused on RCP2.6 and RCP4.5, as these two RCPs represent potential outcomes in line with current climate agreements and policies. RCP2.6 is roughly equivalent to keeping mean global warming to 2°C and in line with the Paris Agreement. RCP4.5 is approximately equivalent to mean global warming of 2–3°C by 2100, and is in line with current unconditional Nationally Determined Contributions (UNDP, 2021). By choosing these two RCPs, we demonstrate that even meeting the Paris Agreement (RCP2.6) has potentially negative consequences for renewable energy and energy systems as a whole across Central Asia; current Nationally Determined Contributions (approximately RCP4.5) could have even more negative repercussions for energy infrastructure.

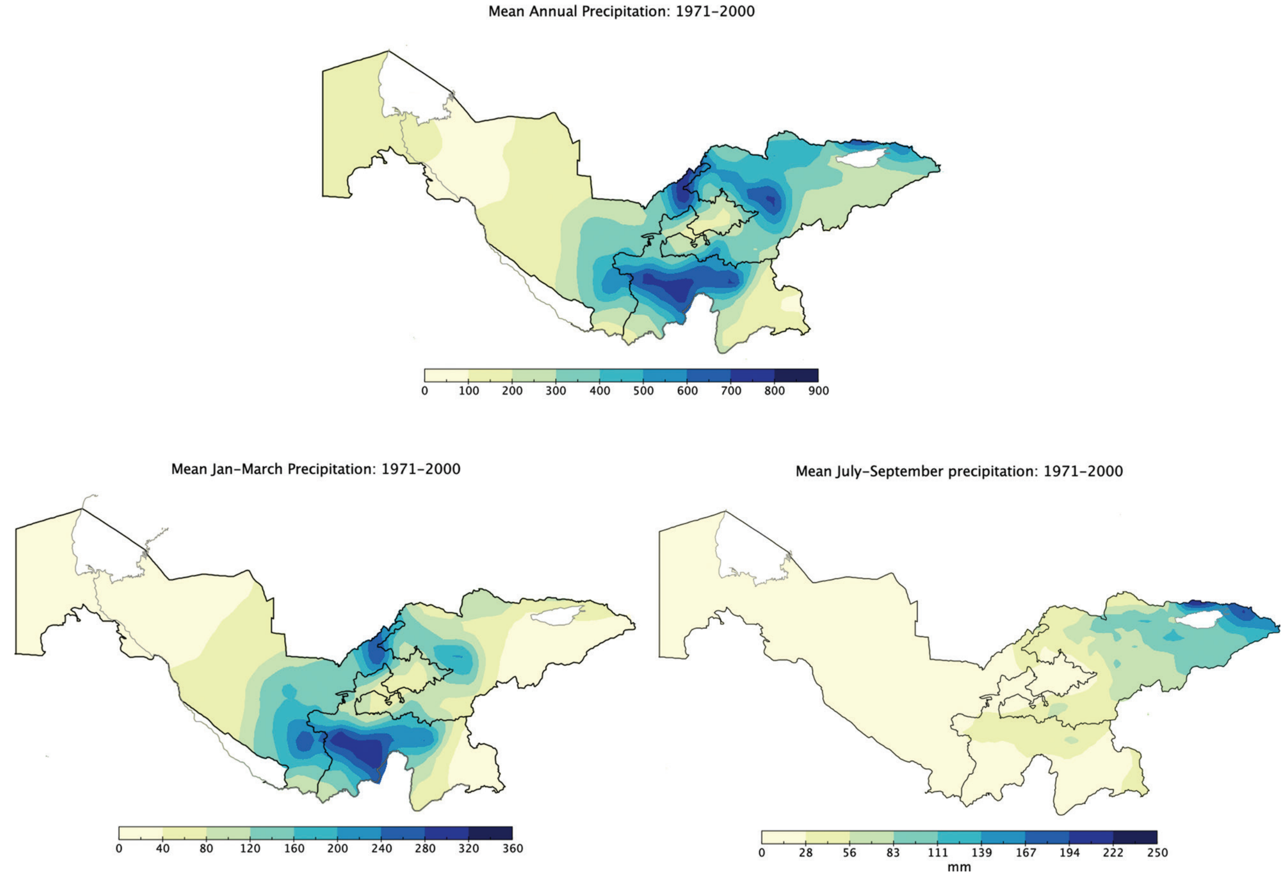
2.2 Recent trends and observations: precipitation, temperature, extremes and glacial melt

The climate of the three countries is diverse: from hot and arid in vast areas of the deserts of Uzbekistan and the southwestern region of Tajikistan, to alpine in the Pamir and Tien Shan ranges in the territories of the Kyrgyz Republic and Tajikistan. There are large spatial variations in mean seasonal and annual precipitation, and minimum and maximum temperatures.

A significant percentage of annual precipitation falls during the winter and spring months across most of the region; only in eastern Kyrgyz Republic in the reaches around the Aksu River Basin does summer precipitation dominate, as seen in Figure 2. Higher annual precipitation totals are concentrated around the Pamir-Alay in Uzbekistan (~800–900 mm/year), the central Pamir mountains of Tajikistan (~1,000–1,800 mm/year) and the northwest, southwest and the area around Lake Issyk-Kul in Kyrgyzstan (~600–1,100 mm/year) (Government of Uzbekistan, 2016; Government of Tajikistan, 2014; 2021; Government of Kyrgyz Republic, 2016). Total precipitation amounts vary by elevation, and orientation (windward or leeward) in the mountains. The western desert of Uzbekistan and the highland plateau east of the Pamir in Tajikistan receive less than 100 mm/year (ibid.).

Statistically significant trends in annual and seasonal precipitation since the 1950s are not detectable across most of the region. There is high

Figure 2 Annual and seasonal mean precipitation 1971–2000



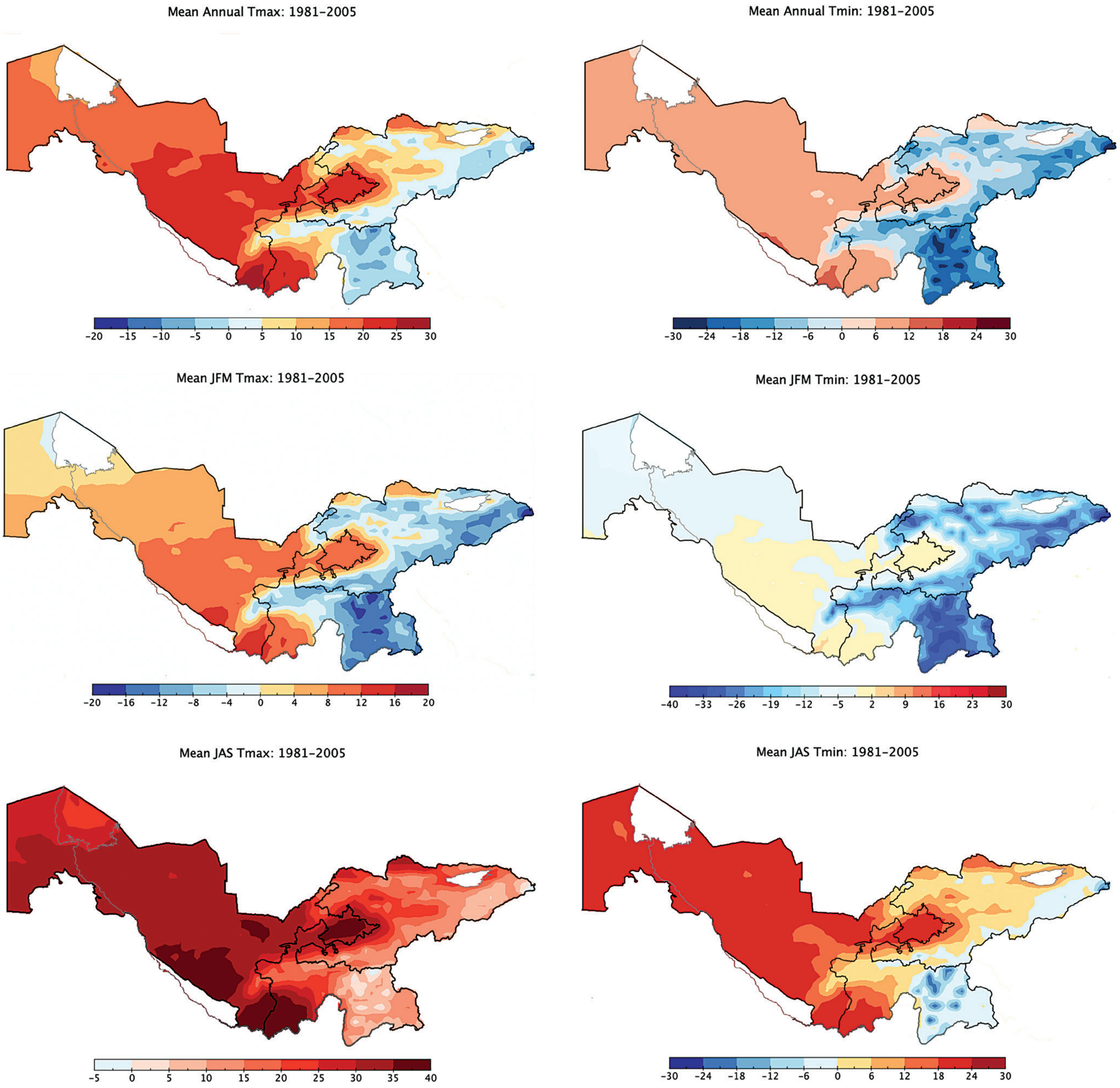
Note: Precipitation values are in mm/year and mm/season. Mean totals were derived from precipitation observation data over the period 1971–2000. Given the spatial diversity of annual precipitation totals, particularly over mountain reaches, the precipitation scale on the maps does not display the totals above 1,000 mm/year as experienced in the central mountains of Tajikistan and some parts of Kyrgyzstan. See text for details.

Source: Authors' calculations using APHRODITE

year-to-year and decadal variability linked with multi-year and multi-decadal climate processes such as the El Niño-Southern Oscillation and the Pacific Decadal Oscillation (Umirbekov et al., 2022). Eastern areas of the Pamirs in Tajikistan have experienced statistically significant increases in winter precipitation since 1979 (Government of Tajikistan, 2014). Small, statistically significant precipitation increases are occurring in the northern Tian Shan in Kyrgyzstan (Government of Kyrgyzstan, 2016), and some small, but statistically insignificant decreasing trends have occurred in south-central Uzbekistan in Bukhara and Kashkadarya provinces (Khaydarov and Gerlitz, 2019). No other statistically significant long-term trends are emerging yet.

There are large spatial differences in daily maximum (T_{max}) and minimum temperatures (T_{min}) averaged over annual and seasonal scales, as shown in Figure 3. The temperature differences are most pronounced over mountainous areas with high topographic relief. For example, daily maximums in Shaartuz, southeast Tajikistan, can be 22°C, while Lake Bulunkul in the Pamirs is experiencing -60°C (Government of Tajikistan, 2021). Uzbekistan has a continental climate across most of the country, with cold winters and long, hot and dry summers. Uzbek annual average maximums range from 10°C to over 30°C (see Figure 3), with July daily maximums approaching 40°C in Termez, Surkhandarya province (Government of Uzbekistan, 2016). Western and north-western parts of Kyrgyzstan are warmer than the eastern parts of the country, with annual T_{max} of 5–20°C; the high Tian Shan along the south/south-east are colder. Similarly, the annual T_{max} of the high mountain reaches in Gorno-Badakhshan is below freezing, in contrast with the plains of Khation.

Figure 3 Annual and seasonal mean maximum and minimum temperatures 1981–2005



Note: T_{max} and T_{min} are in °C, and temperature scales are different for each season and the annual figures. T_{max} in summer exceeds 40°C in parts of Uzbekistan and Tajikistan, and is not captured in the legend scale. Winter extremes in parts of the Pamir of Tajikistan are also not adequately captured in the legend.

Source: Authors' calculations using ERA-Interim temperature data

Climate change impacts are beginning to be felt across the three countries in this study. Clear and statistically significant increases in maximum and minimum temperatures are detected across all three countries and at most elevations. In Tajikistan, decadal rates of average warming between 1976 and 2012 were 0.2°C in autumn, 0.3°C in spring and 0.15°C in winter (Government of Tajikistan, 2014). Mean maximum temperature increases have been particularly pronounced in spring, increasing by about 0.5°C per decade between 1981 and 2015 (Feng et al., 2017). Uzbekistan experienced an average warming of 0.27°C per decade between 1950 and 2019 (Government of Uzbekistan, 2021); rates of warming around the Tashkent and Samarkand regions have accelerated to 0.52°C per decade since 1991 (Kholmatjanov et al., 2020). Mean maximum springtime temperatures around the Aral Sea are now exceeding 40°C, and the number of hottest days has increased from 25 days per year to 40 days per year in some regions (Government of Uzbekistan, 2021). Winter and spring warming of 0.3°C per decade has been observed across much of the Tian Shan in Kyrgyzstan since 1990, with some areas of the country warming by about 0.7°C per decade since 1990 (Siegfried et al., 2012; Government of Kyrgyzstan, 2016).

These widespread increases in mean seasonal maximum and minimum temperatures and the number of extreme heat events are having observable impacts on glacial extent and mass balance, permanent snowfields and snow cover. As a result, the hydrologies of the Pyanj, Naryn and Vakhsh rivers, and other tributaries of the Amu Darya and Sur Darya rivers, are being impacted. Snow reserves and glaciers contribute differently to river run-off depending on the watershed; spring and summer thaw leads to peak flows and some forms of flooding.

2.3 Scenarios: climate change projections for the 2050s

2.3.1 Projections for mean annual and seasonal precipitation and temperature

According to the CORDEX models, climate change shifts in seasons and extremes could be substantial by the 2050s across the three countries.

Both potential increases and decreases in annual and seasonal precipitation totals are possible under both RCP2.6 and RCP4.5 and show strong spatial differences (Figure 4 – displayed as percentage change). Mean annual total precipitation is projected to decrease for the following areas when compared with historical precipitation over the period 1971–2000:

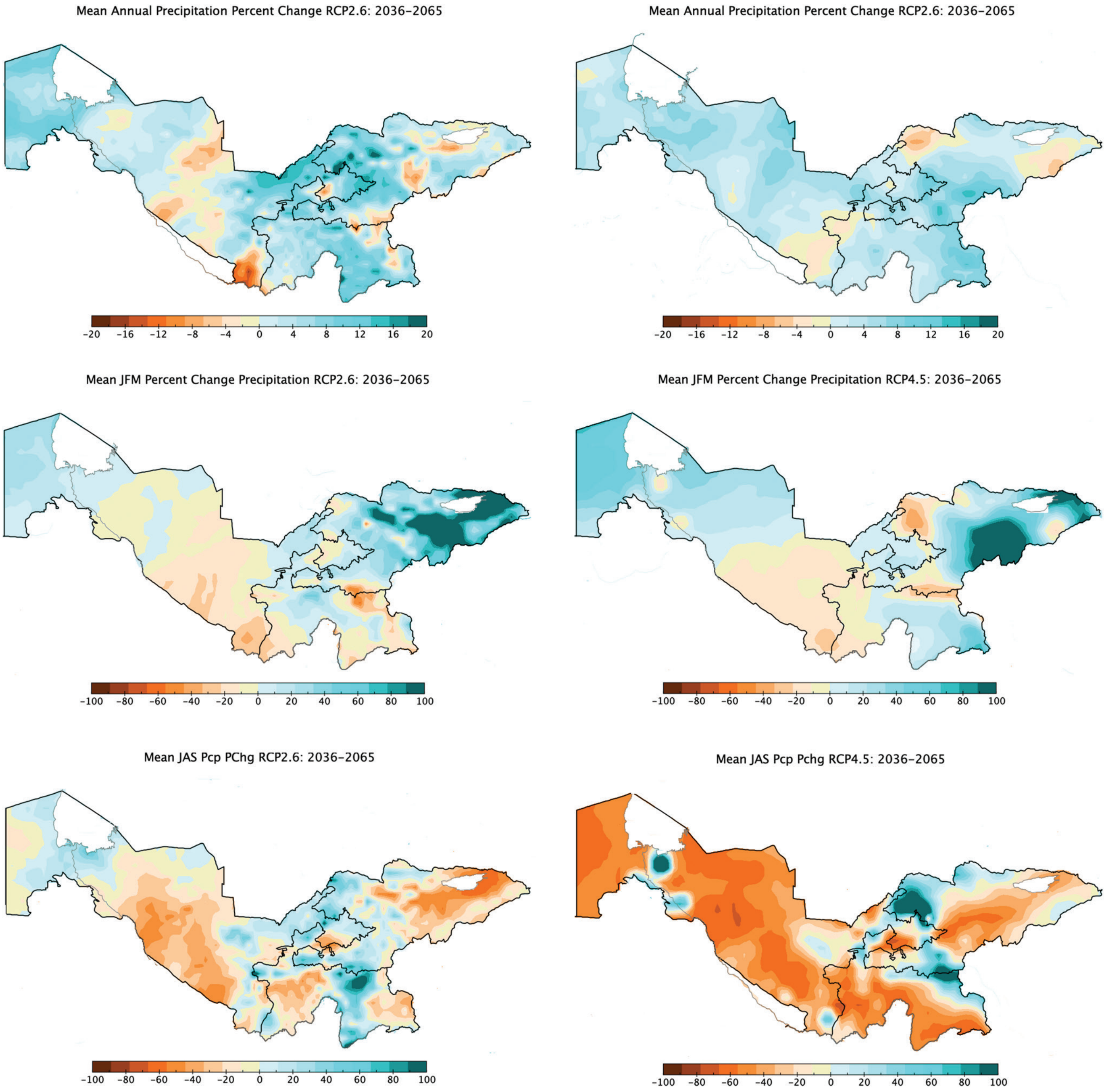
Uzbekistan:
- RCP2.6: Surkhandarya (–6 to –20%); Bukhara and Navoly (0 to –12%)
- RCP4.5: Surkhandarya (0 to –6%)

Kyrgyz Republic:
- RCP2.6: Parts of Chuy, Naryn, Osh and Issyk-Kul (0 to –8%)
- RCP4.5: Issyk-Kul and Talas (0 to –8%)

Tajikistan:
- RCP2.6: Eastern Gorno-Badakhshan (0 to –8%)
- RCP4.5: Southern Sughd (0 to –5%)

Changes in seasonal precipitation indicate that winters (January–March) and summers (July–September) are likely to become drier across a significant portion of the study region. Winter precipitation is projected to increase under both RCPs in Issyk-Kul region, possibly doubling. However, summers are projected to

Figure 4 Projected percentage change in annual and seasonal precipitation 2036–2065



Note: Projected multi-model mean percentage change in average annual and seasonal precipitation amounts under scenarios RCP2.6 and RCP4.5. Anomalies calculated between bias-corrected projections (2036–2065) and observations (1971–2000).

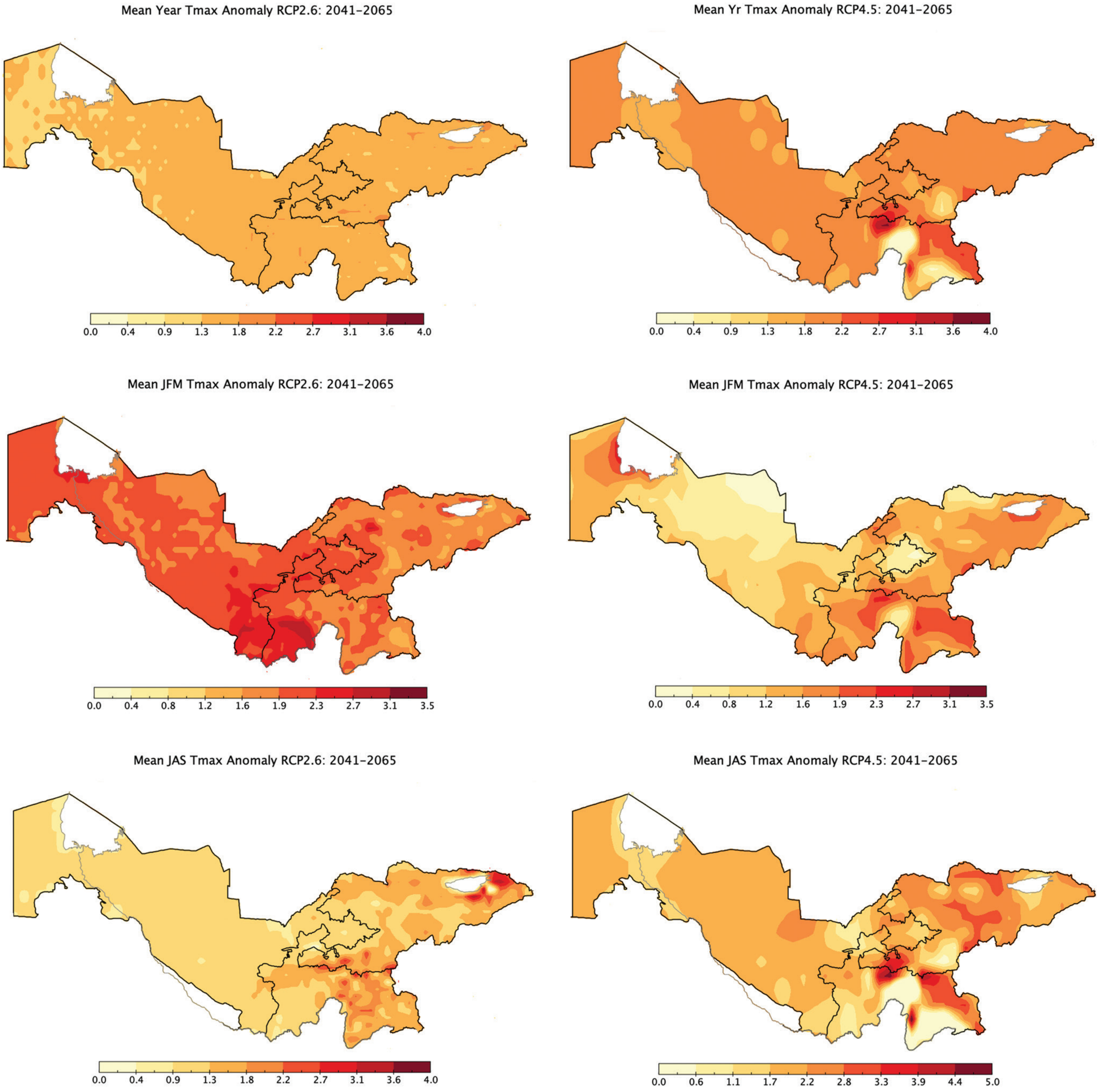
Source: Authors' analysis using APHRODITE and CORDEX data

become considerably drier (RCP2.6: 0 to –50%) with –40 to –70% decreases under RCP4.5.

Decreases and slight increases in annual and seasonal precipitation will be offset by increasing temperatures. There are likely to be increases in annual and seasonal T_{max} and T_{min} (Figures 5 and 6), as well as incidences of extremely hot days above 30°C (Figure 8). Mean annual T_{max} is projected to increase by between 1.3°C and 1.8°C for most of the study area under RCP2.6; under RCP4.5 annual T_{max} could increase by between 1.8°C and 2.2°C for most of the region, with increases of up to 4.0°C projected for the Pamir-Alay and eastern Pamirs in Tajikistan (Figure 5). Winter T_{max} increases are greater under RCP2.6 than RCP4.5, with summers warming more under RCP4.5 than RCP2.6.

Minimum (night) temperatures are also expected to increase on a seasonal and annual basis

Figure 5 Projected mean anomalies in annual and seasonal maximum temperatures 2041–2065



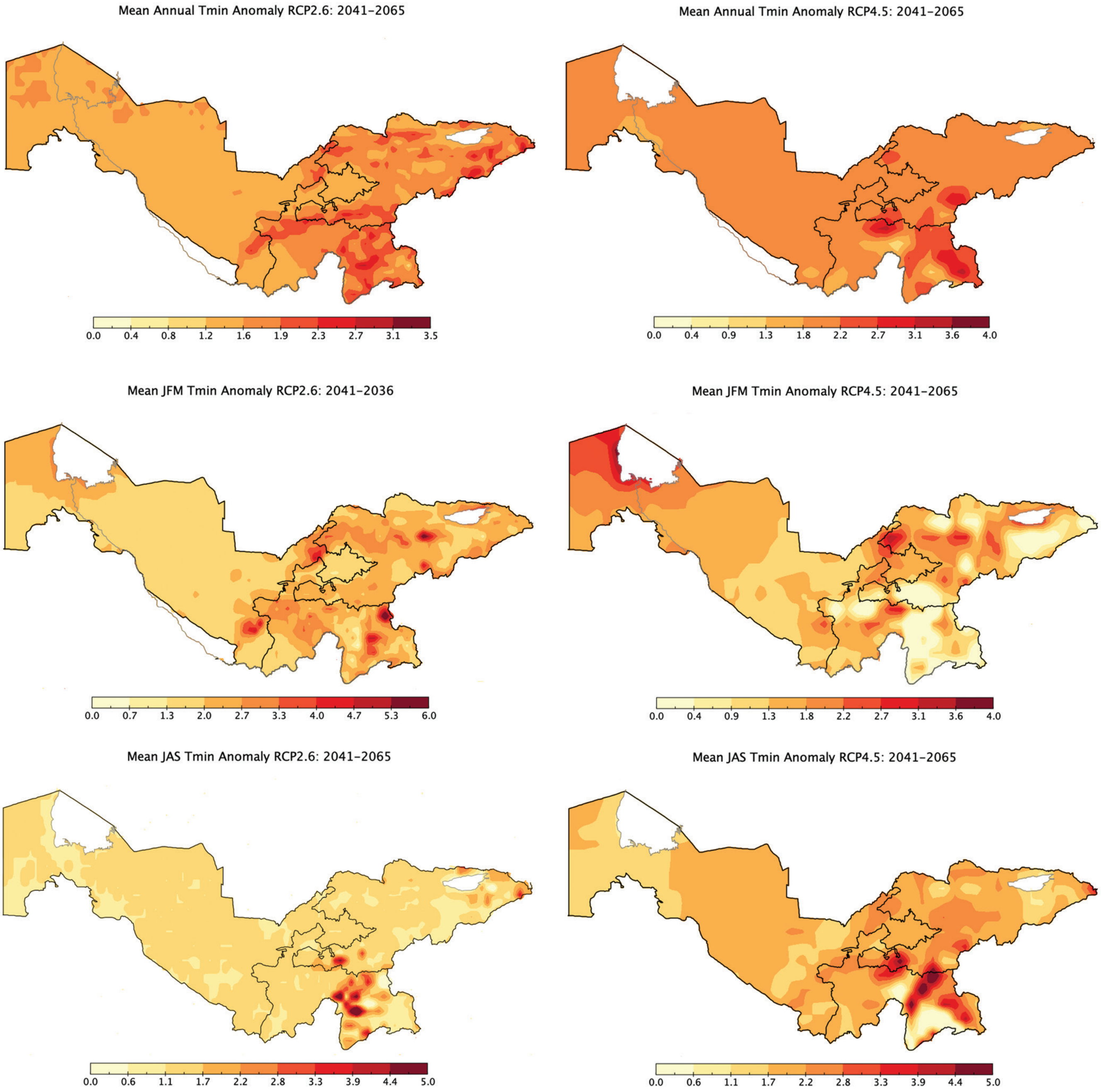
Note: Projected multi-model mean anomalies in average annual and seasonal maximum temperatures (T_{max}, °C) under scenarios RCP2.6 and RCP4.5. Anomalies calculated between bias-corrected projections (2041–2065) and observations (1981–2005).

Source: Authors' calculations from ERA Interim Data and CORDEX data

(Figure 6). Warming of T_{min} is most pronounced over the Pamir, Pamir-Alay and parts of the Tian Shan under both RCPs – mean annual warming of up to 3.1°C under RCP2.6 and 3.6°C under RCP4.5. Other areas could experience increases of between 1.2°C and 2.2°C in minimums by the 2050s.

The temperature increases in all seasons are impacting glacier and snow cover extent, and

Figure 6 Projected anomalies in annual and seasonal minimum temperatures 2041–2065



Note: Projected multi-model mean anomalies in average annual and seasonal minimum temperatures (T_{min}, °C) under scenarios RCP2.6 and RCP4.5. Anomalies calculated between bias-corrected projections (2041–2065) and observations (1981–2005).

Source: Authors' calculations from ERA-Interim data and CORDEX data river hydrology, to various degrees spatially; there is also high intra-annual variability. The Third National Communication of Tajikistan indicated that glaciers are sensitive to temperature changes of 0.5–1°C during the summer (Government of Tajikistan, 2014). MODIS remote sensing data indicate that the Pamir have experienced a mean warming of 0.7–1.2°C per decade since 2002 (Pohl et al., 2017); Tian Shan warming rates averaged 0.1–0.2°C per decade between 1960 and 2007 (Barandun et al., 2020).

Total average glacial extent is estimated to be 30% of what it was in the 1930s in Tajikistan (Government of Tajikistan, 2014); Kyrgyzstan has lost 23%. There is wide spatial variability in glacier mass balance change across the Pamir and Tian Shan mountains (Barandun et al., 2020 and 2021; Pohl et al., 2017; Shean et al., 2020 – see Figure 7). Smaller glaciers at lower elevations are being impacted, and glacier extent has decreased in the Vakhsh, Pyanj and Zerafshan river basins. Across the border in Kyrgyzstan, the Karadarya basin may be glacier-free by the 2050s (Gafurov, 2022). The Naryn and Zerafshan basins could see reductions of up to 80% in glacial extent by 2100 (ibid.).

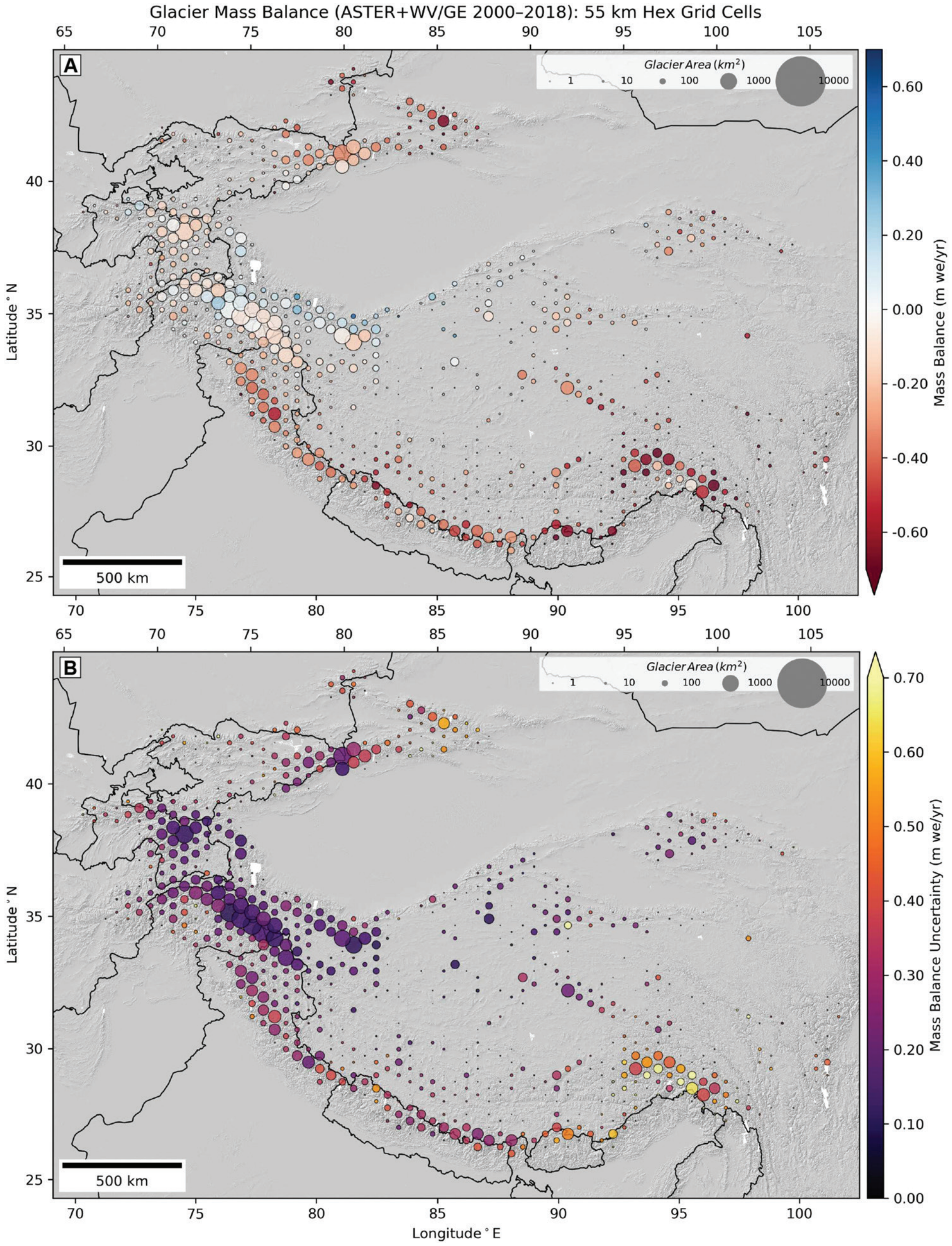
The climate change impacts will have a number of implications for the energy–water nexus. A lack of in situ monitoring requires the use of remote sensing data to estimate trends in glacier change, and makes it difficult to evaluate specific shifts at the catchment level for various tributaries (Pohl et al., 2017). Nonetheless, observations in Kyrgyzstan and Tajikistan indicate that cumulative run-off has increased since 2000 in many catchments (Barandun et al., 2020; Pohl et al., 2017). The potential impacts of climate change are different for each river basin, particularly those in which snow fields or glaciers contribute to baseflows. River baseflows will initially increase as melt increases, but are likely to decrease by 2100, according to models (Barandun et al., 2020). For every glacier and snow reservoir, there is a critical point after which the glacier or snow field will no longer be able to contribute much to river baseflows, leading to decreases in water supply. For smaller river basins, critical points are likely to be reached sooner than for larger basins, but much depends on warming at elevations and the evolution of the degradation of glaciers and/or snow reserves that support flows (Gafurov, 2022). In the Big Naryn, the tipping point is expected in the 2040s; it has already been reached in the Small Naryn. The critical point may occur around 2035 in Naryn Uchterek (ibid.).

Permafrost degradation will increase soil erosion, rockfall, mud floods, and sediment loads in rivers. There is also the potential for more spring flood events due to an increasing number of rain-on-snow events at low to middle elevations, in addition to the risk of glacial lake outburst flood in some basins. Warmer temperatures in spring are increasing avalanche risk in low mountain zones (Government of Uzbekistan, 2016). All of these changes will create risks for hydropower systems and water resource management.

2.3.2 Projected changes in extreme event intensity and frequency

There are a variety of climate extremes relevant to the damage thresholds of generation and transmission infrastructure, as well as demand. During the periods between autumn and spring, extreme cold spells, icing events, and rain-on-snow events in the mountainous areas, can reduce generation and transmission efficiencies and lead to damage. For instance, ice build-up with or without high winds on transmission lines can cause lines to sag and snap, and transmission towers to collapse, among other impacts. Energy companies across the three countries have experience of winter extremes and take them into consideration when designing, operating and maintaining energy infrastructure, as reported in national consultations for this study.

Figure 7 Glacier mass balance loss 2000–2018



Note: Glacier specific mass balance between 2000 and 2018

Source: Shean et al. (2020: Figure 4a)

Infrastructure planning is less robust for extreme heat events and the subsequent direct and cascading risks that could result. Therefore, this report focuses on projections of two extreme heat-related indices – the number of days in a season where daytime temperatures exceed 33°C[1]

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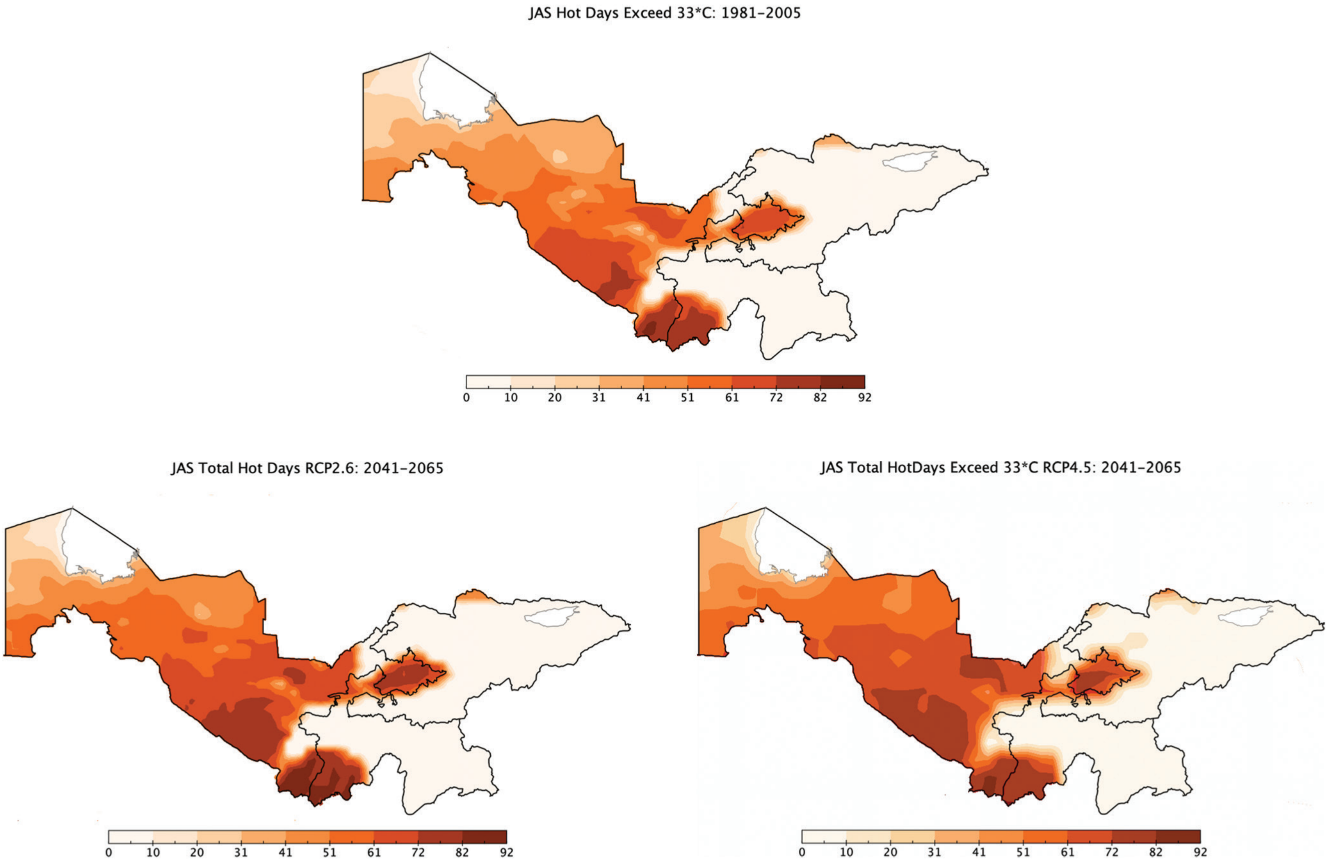
[1] We are using this human health-based extreme heat threshold, as the standard 35°C threshold is applicable to healthy males. Individuals with health conditions such as diabetes, pulmonary or heart disease or cancer, pregnant women, children and elderly people may have lower thresholds before developing heat stress and stroke. Outdoor labourers (e.g. farmers and construction workers) and those engaged in moderate to heavy physical activity without suitable cooling will also develop heat stress sooner (Ebi et al., 2021; Opitz-Stapleton et al., 2016).

Figure 8 July–September extreme heat days



Note: Number of days exceeding 33°C during July to September for 1981–2005 (historical) and projected (2041–2065).

Source: Authors' calculations from ERA-Interim data and CORDEX data

and the number of nights with temperatures exceeding 27°C.[2] We also include a snapshot of potential changes to 24-hour extreme rainfall events by intensity and duration for select geographies, and a discussion on shifts to flood dynamics under a changing climate.

In the past (1981–2005), only southern Uzbekistan (Surkhandarya, Kashkadarya and Samarkand oblasts), southern Tajikistan (Khation) and the Fergana Valley experienced 60 or more days exceeding 33°C between July and September (analysis of ERA-Interim data). By the 2050s (2041–2065), the spatial extent increases for areas likely to experience 60 or more days exceeding the hot day threshold under both RCPs (Figure 8). Under RCP2.6, most of Bukhara and a swath extending from southern Navoi eastwards are

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[2] The US National Weather Service set a night temperature threshold of 27°C (Robinson, 2001). Average relative humidity is high in regions across the three countries. Additionally, humidity often increases at night as temperatures cool; at a relative humidity of 80% and T_{min} of 27°C, this equates to a heat index of 29°C. Temperatures above 27°C, especially when factoring in higher humidity, can lead to heat stress and dehydration (even at night). Even when relative humidity is low, at T_{min} above 27°C, the body still has difficulty cooling down; this can lead to health problems as the physiological impacts of persistent hot days and nights mount.

affected; under RCP4.5, the areas impacted extend further north, and more than half of Uzbekistan faces hot temperatures. Major population centres in all three countries, such as Tashkent, Jizzakh, Osh and Bokhtar, will be impacted. Additionally, the length of the hot season could potentially extend, starting in April and extending into October in some locations. The geographic extent experiencing warm nights during the late spring and summer also expands under RCP2.6 and RCP4.5 (not shown).

It was beyond the capacity of this report to analyse changes in the strength of extreme wind bursts, sustained gales and hail due to climate change for the three countries. In a previous study, we analysed shifts in the intensity and frequency of 24-hour extreme rainfall events for area-averaged zones in each country by the 2050s for RCP4.5 and RCP8.5 (Opitz-Stapleton, 2021). Table 2 shows changes in daily extreme rainfall events for select provinces or regions where major energy infrastructure exists or is planned (see next chapter for exposure details).

Table 2 Changes in daily extreme rainfall intensities and frequencies

Return period (years)	Observed	RCP4.5
Kyrgyz Republic: Jalal-Abad		
20	1.41	1.72
50	1.63	1.96
100	1.80	2.14
Tajikistan: Gorno-Badahkshan oblast		
20	0.52	0.66
50	0.59	0.76
100	0.64	0.83
Uzbekistan: Jizzakh oblast		
20	1.42	1.85
50	1.68	2.14
100	1.88	2.36

Note: Projected changes in area-averaged 24-hour extreme rainfall intensities for 2036–2065 (the 2050s) as compared to historical (1971–2000) extremes. Values are in mm/hr. Extreme event analysis conducted in a previous study by the author.
Source: Opitz-Stapleton (2021), unpublished analysis for TA-9878 REG

3 Climate risk screening: exposures, sensitivities and risks

3.1 Exposure

3.1.1 Historical generation and transmission

In Kyrgyzstan and Tajikistan, hydropower plants (HPPs) dominate generating capacity. As of 2021, 5,406 MW of Tajikistan's total 6,124 MW generating capacity was hydropower (MoEWR, 2022). Kyrgyzstan had 3,034 MW of hydropower generating capacity, out of a total 3,896 MW (NSC, 2022). Uzbekistan is currently more reliant on gas- and coal-fired thermal power plants (TPPs), with wind, solar and hydropower constituting less than a third (2.25 GW) of total generation capacity of 15.6 GW (MoE, 2022).

Generation and transmission infrastructure are ageing across the region. In Uzbekistan, the average age of TPPs and HPPs is 60 years. Two utility-scale solar installations (solar arrays generating more than 1 MW), one HPP and one gas TPP have been constructed in the last five years. Kyrgyzstan's HPPs and coal-fired TPPs are also an average of 60 years old, with additional smaller-scale HPPs coming online in the last 10 years. Tajikistan's HPPs larger than 1 MW capacity range in age from 4 to 86 years; a new coal-fired TPP was constructed near Dushanbe six years ago (MoEWR, 2022).

Historically, much of the generation and transmission infrastructure across the three countries (and southern Kazakhstan and Turkmenistan) was linked under the Central Asian Power System (CAPS) instituted during the Soviet era. There are multiple transmission lines connecting countries and the region, though some countries have been disconnected from other countries at various points since 2000.

There were and are location-specific seasonal dependencies in generation capacity. Those countries more reliant on HPP – Tajikistan and Kyrgyzstan – have higher generation capacity in late spring through early autumn, when river flows along the Vakhsh and Naryn (as well as other waterways) are high due to melting snowpack. Through CAPS, seasonality in the summer HPP generation capacity of upstream countries (Tajikistan and Kyrgyzstan) was offset by TPP generation in other seasons in the more fossil-fuel-rich countries (Uzbekistan) (Vinokurov et al., 2021). Ageing infrastructure and differences in management of generation between the hydropower- and fossil fuel-dominant countries are contributing to load imbalances and blackouts in the winter (ibid.).

3.1.2 Future exposures

All three countries have pledged an expansion of non-conventional (solar and wind) and conventional (hydropower) renewables to various degrees.

Kyrgyzstan: The *National Development Strategy 2018–2040* outlines priorities for the energy sector, which include improving energy efficiency while providing energy security by using HPP potential, increasing the share of renewables (solar, wind and storage HHPs) to 10% of the energy mix, and 'gasification' (National Council for Sustainable Development of Kyrgyz Republic, 2018). The *Green Economy Programme 2019–2023* emphasises the need for government policy to shift towards stimulating energy efficiency and saving, and renewable energy production. Targets of no less than 50 MW of renewable energy, including solar and wind, are set for areas where they may be more cost-competitive than transmission through the national network, accounting for the projected growth in energy consumption through 2040 (Ministry of Economy and Commerce of Kyrgyz Republic, 2019a). The concept for the *Development of the Fuel and Energy Complex until 2030* will be finalised during the duration of the programme (Ministry of Economy and Commerce of Kyrgyz Republic, 2019b).

Kyrgyzstan is rehabilitating major HPPs in the Jalal-Abad region (the 1,200 MW Toktogul above Karakol City, the 120 MW Kambar-Ata 2, and the 180 MW Uch-Kurgan near Tash-Kömür – all on the Naryn River), and one in the Naryn region (the 44 MW At-Bashy). The rehabilitation efforts are in collaboration with the Asian Development Bank and are removing silt and sediment, as well as replacing ageing equipment. The country has plans for two additional HPPs – the 25 MW Bala-Saruu (Russian-Kyrgyz Development Fund) in the Talas region and the 18 MW Karakul (Chakan GES) in the Jalal-Abad region. Construction is expected to commence this year on three solar plants (type unspecified) with installed capacity ranging from 125 MW to 500 MW, and one wind farm (10 MW). The locations of these renewables will be scattered throughout the Issyk-Kul and Chuy regions. The government acknowledges that climate change will exacerbate existing energy problems 'by reducing hydropower output' (Government of Kyrgyzstan, 2016), with outputs of HPPs located in small river catchments projected to decrease by 19% under a 2°C warming (Government of Kyrgyzstan, 2020) – the RCP2.6 scenario mentioned in the previous chapter.

Tajikistan: Tajik energy priorities are articulated in the *National Development Strategy of the Republic of Tajikistan 2030*, with energy security and efficient electricity use listed as one of four key priorities (Government of the Republic of Tajikistan, 2016). For the electricity sector, the strategy envisages development based on the '10/10/10/10' concept: (1) increased design capacity of the electric power system to 10 GW; (2) annual electricity export to neighbouring countries of 10 billion kWh; (3) diversification of capacity of the country's electric power system by at least 10% by increasing the capacity of other energy sources, including coal, oil, gas and renewables; and (4) a reduction in electricity losses in the country to 10% (ibid.). The *Power Sector Development Master Plan,* with support from the Asian Development Bank (ADB), is the main strategic document guiding the development of the energy sector (ADB, 2017). The Master Plan did not consider wind or solar power as priority supply options, with a caveat that they may become more attractive with technological improvements and cost reductions.

While Tajikistan continues to expand HPP planning, it has also been diversifying its energy portfolio to construct solar and wind parks since the 2017 Master Plan. In collaboration with the ADB, the World Bank, the United States Agency for International Development, and South Korea, the country is constructing small- to larger-scale solar power ranging in installed capacity from 0.2 MW to 200 MW. The projects are located throughout the country, in Sughd, Khation and Gorno-Badakhshan. It also has been repairing and upgrading existing HPP, transmission and distribution systems since the early 2000s.

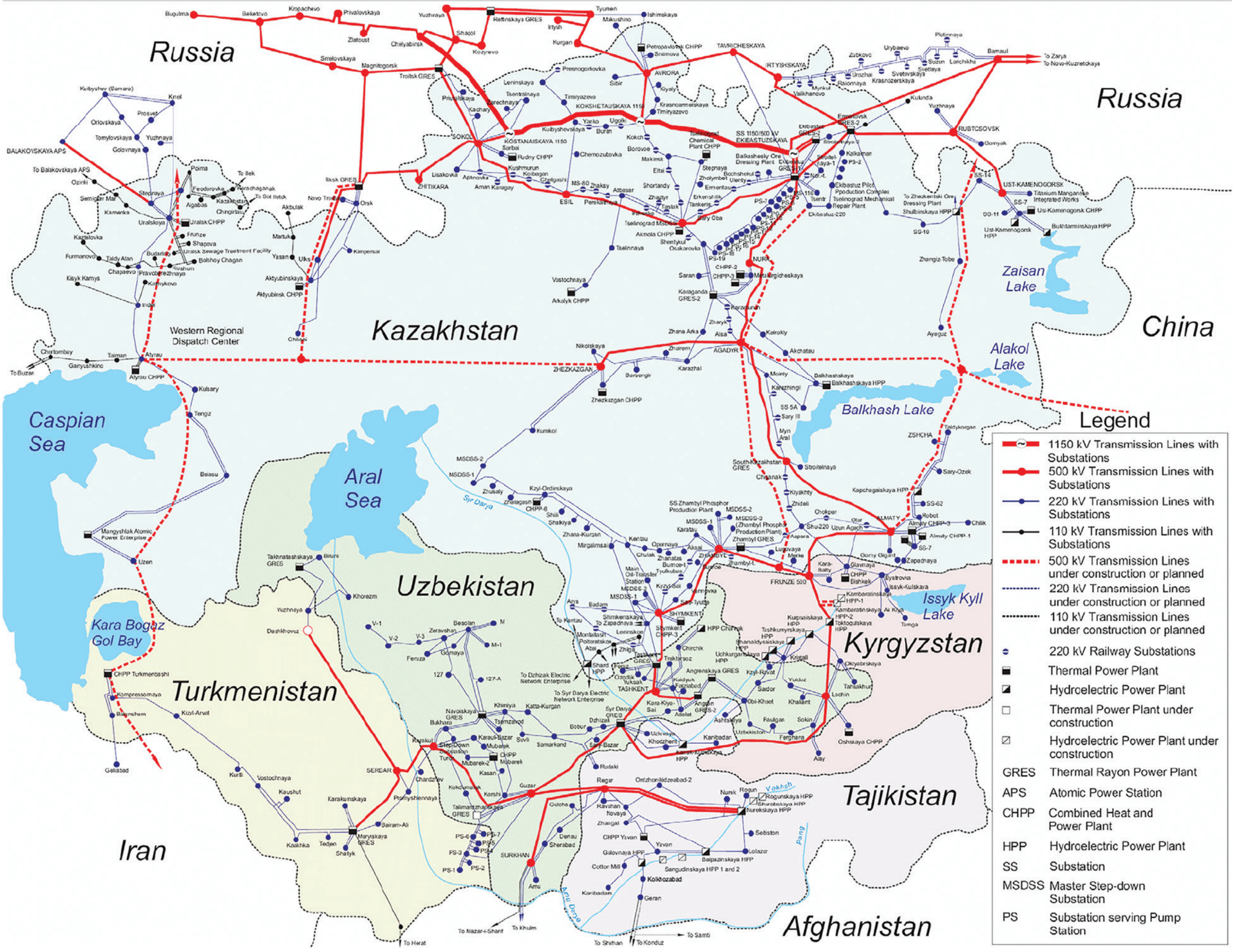
Uzbekistan: According to the *Strategy on the Transition of the Republic of Uzbekistan to the 'Green' Economy for 2019–2030*, Uzbekistan aims to increase its share of renewables in total electricity generation to over 25% by 2030, with electricity generation capacity expected to expand 2.5 times to double annual production by 2030 (President of the Republic of Uzbekistan, 2019). It also emphasises the modernisation and restructuring of the power supply system with the introduction of a system of decentralised generation of electricity based on renewables to increase energy efficiency and the reliability of power grids. This also includes installing modern solar and wind power plants with a total capacity of 8 GW as a priority for the development of the electricity industry.

Solar and wind power plants are currently at various stages of development. Numerous solar photovoltaic (PV) plants (not concentrated solar) and wind farms with total installed capacities ranging from 100 MW to 1,000 MW are being developed in collaboration with the ADB, International Finance Corporation/World Bank, the European Bank for Reconstruction and Development, Masdar (UAE), ACWA Power (Saudi Arabia) and the Phanes Group (UAE). Such facilities will be located in the regions of Surkhandarya, Kashkadarya, Bukhara, Jizzakh, Namangan, Khorezm, Samarkand, Navoi and Fergana, and the Karakalpakstan Republic – in short, throughout the country.

Regional interconnectedness: Some major regional transmission projects include CASA-1000 to construct a 500 kV line between Tajikistan, Kyrgyzstan, Pakistan and Afghanistan, whereby Pakistan would receive energy in the summer to assist with its peak demand.

When looking at the map of existing and planned infrastructure as of 2017 (Figure 9), the exposure of individual HPPs, wind farms and solar PV parks,

Figure 9 Existing major energy infrastructure, 2017



Note: This map is from 2017 and does not show all of the hydropower and utility-scale solar and wind projects that are under construction or planned by the three countries, the CASA-1000 lines or other planned regional transmission.

Source: GENI (2017)

TPPs and regional transmission systems to the climate change hazards outlined in the previous chapter is clear.

3.2 Sensitivities and capacities

3.2.1 Sensitivities: growing demand, general operational thresholds

Demands, inefficiencies and losses are sources of sensitivity in national and regional energy systems. Energy efficiencies are currently low across the region and losses are high (Panwar et al., 2022). Demand for electricity in all three countries has grown steadily since 2000 (see Table 3) due to population increases and growing and diversifying economies without (historically) energy efficiency and demand management policies (World Bank, 2020).

There are some seasonal variations in demand, with irrigation pumping consuming significant electricity between April and September, given that agriculture is estimated to account for approximately 45%, 19% and 26% of total employment in Tajikistan, Kyrgyzstan and Uzbekistan, respectively (ILO, 2022). Water demand for irrigation coincides with the dry months – roughly April to October; disruptions to energy supply due to drought or other hazards impact the ability to pump water for irrigation. The rise in demand due to cryptocurrency mining in Kazakhstan and technological diversification throughout the region represent newer demand trends placing a strain on the existing system.

Table 3 Electricity consumption trends

Country	2000	2010	2019
Kyrgyzstan	8.3	7.5	12.6
Tajikistan	13.4	14.3	15.4
Uzbekistan	43.8	41.8	60.1

Note: Values are in TWh.
Source: IEA (2022)

Table 4 Electricity demand projections

Country	2022	2025	2030
Kyrgyzstan	–	–	–
Tajikistan	20.4	22.7	26.9
Uzbekistan	76	93	138

Note: Values are in TWh.
Source: Tajikistan: Ministry of Energy and Water Resources; Uzbekistan: Ministry of Energy

Demand for electricity will increase in all three countries (Table 4), though demand projections beyond 2030 are not readily available. Tajikistan's *National Strategy for Adaptation to Climate Change up to 2030* acknowledges that the need for irrigation will grow, due to the increasing frequency of drought (Government of Tajikistan, 2019). Peak demand and its duration (hours per day) have been demonstrated to increase during heatwaves in multiple countries. In Pakistan, demand increased by 109.3 TWh per 1°C above ambient temperatures of 30°C (Ali et al., 2013). The increase in energy demand for cooling during heatwaves was estimated to be 25% for Uzbekistan and Tajikistan (Petersen et al., 2021a; 2021b), though no calculations were presented on how the increased demand was estimated or whether demand for greater irrigation pumping was factored in. Further peak demand forecasting for the countries is needed.

Beyond demand, and the strains it can create on generation, transmission and distribution, other sensitivities are related to the operational requirements and thresholds of particular infrastructure.

Solar PV and concentrating solar power (CSP): The expected lifetime of utility solar PV parks and small-scale installations – the type of solar currently planned in the three countries – is 25–40 years (NREL, 2022). Therefore, solar PV installed now and before 2030 will still be operational in the 2050s, the period covered in the climate change scenarios analysis. Solar PV has temperature, dust and limited water sensitivities. Solar PV cells convert only some of incoming solar radiation into energy, and the rest is absorbed as heat. Energy efficiency conversion is dependent on solar cell composition and solar irradiance, as well as ambient air temperatures, wind speed and other weather conditions. On hot days (above 25°C), conversion efficiency decreases; rates of decrease depend on cell composition (Kaldellis et al., 2014). There is an increased likelihood of dust storms in the future due to higher evapotranspiration. Dust reduces solar PV potential, and can cause scouring of panels and equipment. Solar PV and CSP have various water requirements for cleaning; efficiency can drop by up to 30% over a month due to dust (Panat and Varanasi, 2022). CSP requires water for cooling if a wet- or hybrid-cooling system is used. The total water requirement for utility-scale solar is still much lower than for TPPs (Klise et al., 2013). Finally, an intensification of storms is likely in a warmer climate. The winds and hail associated with such storms could cause increasing incidences of damage to solar installations.

TPP – nuclear, coal, gas and oil: The expected lifetime of TPPs ranges from 60 to 80+ years; therefore, TPPs built now will have to contend with possible climate changes in 2100. TPPs are sensitive to extreme heat events, drought and flooding. They often require significant amounts of water for generation and cooling, far exceeding the amounts required for solar and wind. Cooling water in plants with Once-through Cooling Systems is discharged into local waterways, impacting aquatic ecosystems; during heatwaves the impacts of warmer discharges are magnified. (Closed-loop Cooling Systems require less water and have minimal discharges). TPP output is reduced in hot ambient temperatures, with estimates ranging from -0.4% to -0.7% per 1°C increase in ambient cooling water above operating thresholds (Cronin et al., 2018). Drought, especially when concurrent with heatwaves, can reduce water quality and quantity, contributing to corrosion of infrastructure and leading to reduced output due to insufficient water for operations (Dyreson et al., 2022). Flooding can damage and destroy infrastructure, and disrupt supplies of coal, oil and gas by damaging or disrupting transportation networks (Opitz-Stapleton et al., 2021). If a TPP is damaged or destroyed during a flood or a storm, contamination of surrounding ecosystems is also possible. It is beyond the ability of this report to evaluate the specific climate sensitivities of individual TPPs in each of the study countries.

Wind farms: The expected useful lifetime of wind installations is approximately 20 years (NREL, 2022). Projects installed before 2030 will be operational into the early 2050s and exposed to the hazards outlined in the previous chapter. Cold events contributing to blade icing are likely to decrease in frequency (Pryor and Barthelmie, 2013), though they will continue to be problematic in mountainous areas or those with higher humidity near lakes. However, heatwaves can also damage components of wind turbines and towers. The standard operating temperature thresholds of turbines range from -30°C to 50°C, depending on the manufacturer. Turbine systems may shut off at ambient temperatures approaching operational limits, to prevent damage, though exact specifications are hard to find. Increases in erratic winds and increasing wind speeds due to more intense storms under climate change have been studied more in terms of impacts on overall seasonal generation and damage (Solaun and Cerdá, 2020; Abdin et al., 2019). Depending on operating thresholds, wind plants have to shut off turbines to avoid excessive loads and damage to equipment during extreme winds (Das et al., 2020).

Hydropower: River hydrology – baseflows, peak flows and their timing, and water quality such as sediment load – are crucial to the operation of both run-of-river and storage HPPs. These factors are themselves influenced by the existence of upstream storage HPPs, and are transmitted through the entire river basin and all reservoirs on it. Any changes in river hydrology immediately impact the generation capacity of run-of-river HPPs; storage HPPs can variably buffer some hydrological changes, depending on storage capacity. Low flows due to drought, especially concurrent with heatwaves, and/or higher evaporation due to warmer seasons, shifts in the timing of peak flows, as well as flash flooding due to extreme rain events or rain-on-snow events in colder months will impact HPP generation (Kao et al., 2016; Schaefli, 2015). Sedimentation of hydropower dams is also a key challenge, reducing both generation and storage capacity. Nurek HPP has experienced a reduction in installed capacity of 20–25% due to sedimentation and ageing infrastructure (World Bank, 2020).

Depending on the rate and spatial extent of glacier and snowmelt, and increasing sediment loads due to permafrost melt and erosion, hydropower potential may initially increase for the next three or four decades but is likely to decrease towards 2080–2100, depending on the catchment (Barandun et al., 2020; Gafurov, 2022). Tajikistan and Kyrgyzstan have been releasing water from reservoirs in winter to cover seasonal generation deficits, but this has led to reduced generation and water supply in the subsequent year (Vinokurov et al., 2021). Changes in reservoir operation impacts downstream reservoirs and river–groundwater ecologies.

HPPs are also a source of geopolitical risk, which could be exacerbated depending on how individual countries manage water resources in consultation with downstream countries in the face of climate change. There have historically been tensions and disputes between the three countries with regard to water for irrigation and hydroelectricity production along the Syr Darya and tributaries such as the Naryn, or the Amu Darya. Toktogul reservoir in Kyrgyzstan and Nurek reservoir in Tajikistan reportedly control 60% of current Central Asian storage capacity between them (Sakal, 2015); management of these has caused disagreement with neighbouring countries.

Transmission, distribution and substations: The expected lifetime of these types of infrastructure vary, from approximately 35–45 years for substations to 50 years for transmission lines. The CASA-1000 transmission system is likely to still be operational in the late 2070s, for instance. While ice build-up and wind disruptions will continue to pose risks to the integrity and capacity of transmission and distribution lines, extreme heat events will increasingly pose problems throughout the interregional transmission and local distribution networks. The number of cold days is projected to decrease but will still be problematic for medium to high elevations. The capacity of transmission and distribution lines is reduced during extreme heat events, and subsequent higher demand, by up to 20% (Burillo et al., 2018). Load rebalancing to other transmission lines is then necessary, and the increased power loads can cause these to heat faster in extreme events and also droop, leading to cascading loss of transmission and distribution. Transmission and distribution lines are also vulnerable to excessive winds (Cai et al., 2019). This can lead to cascading instabilities through the grid.

3.2.2 Capacities: current risk management policy

All three countries have disaster risk management policies and government ministries or departments with various risk management mandates according to ministry function. Existing national disaster risk management frameworks tend to focus on disaster response and early warning. Yet all three countries have affirmed commitments to climate mitigation and adaptation, with national adaptation strategies at various stages of development and approval. However, actual capacities and workable strategies to implement climate risk management (adaptation) into sectoral planning and management remains nascent.

Tajikistan's 2014 *Prevention and Elimination of Emergency Situations* outlines emergency response, disaster early warning and planning for categories of emergencies, but does not specifically mention climate change risk management. Within the policy, the Ministry of Energy and Water, whose mandate includes HPPs, is instructed to develop 'flood prevention measures' and 'emergency prevention and response in energy supply emergency situations' (Government of Tajikistan, 2014). A new *National Strategy on Disaster Risk Managemen*t is under preparation and will mention the importance of climate change in disaster risk management. Tajikistan's *National Climate Change Adaptation Strategy to 2030* outlines priorities in four sectors: energy, agriculture, water resources and transportation, and cross-cutting areas (Government of Tajikistan, 2019). Actual climate risk management implementation strategies in and across sectors, and capacities for stronger institutional coordination within and between government bodies around planning and implementation need to be built. The Government of Tajikistan is aware of the need and has been working with the United Nations Development Programme (UNDP), the World Bank, the European Bank for Reconstruction and Development, ADB and others to improve climate risk management through a number of programmes (Government of Tajikistan, 2020). Strengthening the capacity of the Ministry of Energy and Water and energy company personnel to conduct energy-water climate risk assessments and incorporate risk considerations is one priority under the National Strategy and in Green Climate Fund interventions.

The Kyrgyz Republic has undergone a few governance changes in the past decade that have impacted disaster risk management. It is looking to develop its disaster resilience programme and has recently been engaged in updating its national strategic concept. Kyrgyzstan has adopted a strategy for protection from emergencies for 2018–2030, with the priority of investing in disaster risk mitigation measures to strengthen coping capacity. Under its 2013 *Priority Directions for Adaptation to Climate Change*, an overarching adaptation framework was established to strengthen institutional cooperation and provide guidance on climate risk assessment methodology in priority sectors, as well as requiring sectoral adaptation plans (Government of Kyrgyzstan, 2019). The energy sector was not required to develop an updated plan, as it had developed one previously; the sectoral plans developed under the 2013 priorities lapsed in 2017 (ibid.). A copy of the pre-2013 energy sector climate plan was not found for this study and could not be assessed, and it is also likely to have lapsed. Kyrgyzstan is currently developing its *National Strategy and Climate Change Adaptation Plan* in collaboration with UNDP through the Green Climate Fund, with disaster management and agriculture/irrigation water reportedly among the priority sectors. The National Adaptation Plan updating process is expected to conclude in August 2023.

In **Uzbekistan**, the Ministry for Emergency Situations is the executive body responsible for coordinating disaster risk management and recovery efforts at the national level; the Cabinet of Ministers determines financial reserves for disaster recovery. The State System for Prevention and Action in Emergency Situations has been created and is being developed. It combines into a single system the governing bodies, forces and means of republican and local authorities, enterprises, institutions and organisations whose powers include solving issues of protecting the population and territories from emergencies. It is designed to organise and implement measures in the field of prevention and elimination of emergency situations, ensuring the safety of the population in the event of their occurrence, protecting the natural environment and reducing damage to the economy in both peacetime and wartime.

The State Emergency Service consists of territorial and functional subsystems and has three levels: republican, local and object. Each level of the State Emergency Service has:

- the governing bodies of the State Emergency Service
- daily management bodies of the State Emergency Service
- forces and means to respond to emergency situations
- reserves of financial and material resources to respond to emergency situations
- warning systems, communications, and automated control and information support systems.

Uzbekistan has developed a *Strategy of the Republic of Uzbekistan until 2030*, which is under consideration by the government and covers the issues of reducing the intensity of greenhouse gas emissions, taking into account national capabilities and conditions; increasing resilience to climate change and disaster risk management; strengthening adaptation measures and actions; and others. In 2020, together with UNDP and the Green Climate Fund, the development of a National Adaptation Plan was launched to plan adaptation measures and actions for the five most vulnerable sectors: water, agriculture, health, housing and emergency management.

Human and logistical capacities: While policies regarding climate and disaster risk management have been put in place in each country, logistical and human capacities to manage risks at individual power generation, substation and transmission infrastructure must also be acknowledged. Improper training of operators, or failure to implement operating procedures – particularly during a hazard or high electricity demand event – can lead to widespread power outages with cascading impacts. For example, a major multi-country outage occurred on 25 January 2022, due to a reported 'accidental disconnection of a major power line in Kazakhstan' (Al Jazeera, 2022).

3.3 Preliminary risk screening: climate change risks to energy infrastructure

The scenarios of climate hazards from Chapter 2 – in combination with the exposure of existing and planned energy infrastructure and general operational sensitivities just outlined – illuminate a number of general[3] direct and cascading climate change risks to the regional energy system. Some of these general risks are described in Table 5 and were drawn from existing climate–energy risk studies in other countries.

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[3] It was beyond the capacity of this study to conduct a semi-quantitative or quantitative risk assessment for individual infrastructure or the regional energy system.

Table 5 Direct and cascading climate risks to energy systems

Climate hazard	Direct risk	Cascading risk
Extreme heat event: *likelihood of 60+ days of Tmax above 33°C during July to September for large swaths of Uzbekistan, and smaller parts of Kyrgyzstan and Tajikistan* (*Figure 8*)	● Leads to higher likelihood of drought and wildfire ● Evapotranspiration of reservoirs increases; water temperatures increase ● TPPs – coal, gas or nuclear – higher cooling water temperatures reduce thermal efficiencies and generation capacity ● Efficiency of solar PV decreases above 25°C ● Efficiency of wind turbines decreases as operation thresholds approached; shutdown to avoid damage ● Metal wiring in transmission lines expands; lines sag, cross and short circuit; transmission reduced and/or power outages ● Energy demand for cooling and irrigation pumping increases	● Widespread generation declines, particularly if heatwave covers a large area ● Voltage drops and load balancing issues ● Load shedding, brownouts and blackouts ● Network failure; short circuiting of transmission or distribution lines triggers wildfires ● Expansion of asphalt in road or rail systems disrupts transportation access to make energy system repairs ● Socioeconomic impacts – disruptions to businesses, homes, water treatment and sewage, hospitals, airports, metros
Meteorological drought and/or overall expected decreases in seasonal precipitation totals: *mean January–March precipitation expected to decrease by 2–30% over parts of all three countries, including the Pamir-Alay mountains* (*Figures 5 and 8*)	● Risk of drought (definition varies by country) ● Impacts of drought are exacerbated by simultaneous heatwaves ● Water availability and quality for TPP operations declines; water temperatures for cooling and discharge increase ● Reservoir storage levels decline, reducing hydropower generation and water releases ● Water availability for solar PV plant construction and operations ● River ecosystems disrupted	● Energy demand for irrigation pumping increases; groundwater overdraft; food prices and security affected ● Energy generation declines, potentially over a large area if drought is widespread ● Load shedding, brownouts and blackouts ● Network failure; short circuiting of transmission or distribution lines triggers wildfires ● Socioeconomic consequences: business disruptions; interruptions to the power supply of residential buildings, water treatment facilities and sewerage systems; disruption to hospitals, airports and metros ● Increasing geopolitical water–energy tensions

Stronger storms with higher winds and hail: *not explicitly analysed*	• Damage to solar panels, transmission lines and towers • Wind turbines shut down to avoid excessive load and damage	• Transport access to repair infrastructure is blocked • Load shedding, brownouts and blackouts • Socioeconomic consequences: business disruptions; interruptions to the power supply of residential buildings, water treatment facilities and sewerage systems; disruption to hospitals, airports and metros.
Higher daytime and night-time temperatures in all seasons accelerate melt of mountain snowpacks, permafrost and glaciers, and impact the water–energy nexus regionally: *Tmax and Tmin increases of up to 1.6–3.1°C in winter and 1.1–5°C in summer over Pamir and Tian Shan; warmer daytime and night-time temperatures in all seasons over the entire study region* (*Figures 6 and 7*)	• Increased likelihood of rockslide, mud floods and avalanche • Shifts in peak flows from late to early summer • Glacial lake outburst flood • Potential for flash flooding due to rain-on-snow events in late winter and spring for lower to mid-elevations • Sediment levels in rivers increase • Warmer water temperatures	• Generation and transmission damaged by rockslide, mud floods or avalanche • Transport access to repair infrastructure is blocked • HPP reservoirs lose storage due to sedimentation; generation declines • Shifting river peak and baseflows require changing HPP operations, particularly for run-of-river or those with small storage capacity, and balancing irrigation demands against water requirements for electricity generation • Increasing geopolitical water–energy tensions
Extreme rainfall events: *multiple regions/ provinces and districts. In many areas, the intensity and frequency of 24-hour rainfall extremes is likely to increase, with what was a 1-in-100-year event becoming a 1-in-20-year event in some of the areas where new generation and transmission infrastructure is planned* (*Table 2*)	• Flooding, particularly in late winter and spring if rain-on-snow events • Increased likelihood of slope instability and collapse; formation of mud flows and landslides • Increased sedimentation in rivers and reservoirs	• Normal operating levels on HPP reservoirs has to be kept lower for flood routing, reducing downstream water availability • Maximum storage capacity of smaller reservoirs breached by excess run-off • Smaller HPP reservoirs have spillway overtopping and open flood gates for routing, thus decreasing storage for summer • Generation capacity of HPPs and TPPs has to be reduced to protect infrastructure • Generation and transmission damage • Transport inaccessibility to make repairs • Load shedding, brownouts and blackouts • Socioeconomic consequences: business disruptions; interruptions to the power supply of residential buildings, water treatment facilities and sewerage systems; disruption to hospitals, airports and metros

Note: General direct and cascading risks extrapolated from the scenarios (Chapter 2); exposure data and general sensitivity and adaptive capacity information from the international literature on climate risks in energy systems as shown below in 'Source'.

Source: Abdin et al. (2019); Cronin et al. (2018); Das et al. (2020); Dyreson et al. (2022); Forzieri et al. (2015); Ibrahim et al. (2014); Kao et al. (2016); Klise et al. (2013); MoEWR (2021); Opitz-Stapleton (2021); Opitz-Stapleton et al. (2021); Sánchez-Sierra et al. (2020); Schaefli (2015); Spath et al. (1999); Vinokurov et al. (2021)

4 Recommendations: opportunities through good practice risk management

Transitions to renewables and a net-zero economy are part of a climate change risk management strategy; temperatures are hotter; the number of extremes greater; and the overall severity of climate change worse under higher emissions scenarios than keeping global emissions in line with the Paris Agreement. However, an all-hazards risk management approach for critical infrastructure, including energy generation, storage, and transmission and distribution lines, is still needed. Electricity demand will continue to increase across the three countries, with growing populations, economic diversification and new technologies coming online. And even at the Paris Agreement targets of keeping mean global warming to 2°C (roughly RCP4.5) or the lower threshold of 1.5°C (approximately RCP2.6), seasons will continue to warm, and the frequency and intensity of extremes will increase.

While this report has focused on climate risks, as the ongoing cascading impacts of the COVID-19 pandemic or the 2021 ransomware cyber-attack against the United States Colonial Oil and Gas Pipeline demonstrate, planning for multiple hazards is necessary. Cyber-attacks against critical infrastructure, such as energy infrastructure, can be wide-ranging – from state-led industrial espionage to disrupt and damage systems, to individual hacker groups stealing data for ransom. Cyber-security requires the involvement of energy–IT security specialists during project design, construction and daily operations to prevent weak points in system design and to address dynamic system vulnerabilities.

We present the following good practice recommendations to assist in taking an all-hazards risk management approach in energy infrastructure. These should not be called 'best' practice recommendations, as globally, countries and energy companies are still learning how to conduct all-hazards risks assessments, revise policies and improve technologies and standards to manage future risks. We have a lot to learn and a long way to go. Nonetheless, enough experience exists from decades of proactive disaster risk management to recommend some good practices for mitigating complex future risks.

Recommendation 1

Update national disaster risk management policies and National Adaptation Plans to require all-hazards risk management for infrastructure, and develop a regional all-hazards risk management framework and guidelines.

Subnational and national disaster, climate and technological risk policies and requirements for environmental impact assessments will have to be updated to require more proactive risk management in the planning, permitting and operation of energy infrastructure. Additionally, given the interconnectedness of the grids between the three countries and others (e.g. Kazakhstan, Afghanistan, Pakistan and China), strengthening the management of climate, cyber and demand risks to energy infrastructure and water through the existing regional body, the Interstate Commission for Water Coordination of Central

Asia (ICWC), the Coordination Dispatch Center "Energy" and national ministries is required. Regional insurance facilities (see Recommendation 7) can also assist in enhancing regional climate and multi-hazard risk management. The ongoing World Bank programme 'Strengthening Financial Resilience and Accelerating Risk Reduction in Central Asia' provides another vehicle for regional risk management cooperation.

While the climate risks to the energy–water nexus have subnational to regional geopolitical implications, it is desirable to begin developing regional all-hazards risk management guidelines and strengthen regional assessments. The ICWC embraces integrated water resource management, and Climate Risks and Vulnerability Assessments were conducted in 2021 for Tajikistan and Uzbekistan under the 'Climate Mitigation and Adaptation Program for the Aral Sea Basin' (CAMP4ASB); these need to be brought together as a regional assessment.

Multiple international frameworks and guidelines exist in addition to those that are being developed regionally, from which the countries could draw. For instance, the 2019 Organisation for Economic Co-operation and Development's *Good Governance for Critical Infrastructure Resilience*, the online US *Climate Resilience Toolkit: Climate Data and Tools for the Energy Sector* and the World Bank's global knowledge products (e.g. the 2016 *Emerging Trends in Mainstreaming Climate Resilience in Large-Scale, Multi-sector Infrastructure PPPs*) offer starting points for revising and developing national and regional frameworks and policies.

Recommendation 2

Require semi-quantitative to quantitative all-hazards risk assessments for infrastructure, and develop a regional energy system assessment.

Resilience in the energy system requires anticipation of future risks and demand, and proactive rather than reactive management. And this requires full semi-quantitative to quantitative climate change and disaster risk assessments (including cybersecurity through the involvement of IT security experts) as part of environmental impact assessments for planned energy infrastructure in each country. While an infrastructure-specific assessment is required, it must be embedded within a basin or system-wide assessment. An individual generation or transmission infrastructure is part of the larger regional water–energy system.

Guidebooks and tools for conducting climate risk assessments exist, some of which have been highlighted in this study (Willows and Connell, 2003; Sanchez-Sierrá et al., 2021; Forzieri et al., 2015; Bertoldi et al., 2018; Dyreson et al., 2022). A hydropower-specific guide, the *Hydropower Sector Climate Resilience Guide* (IHA, 2019), was developed with support from the European Bank for Reconstruction and Development, the World Bank and the Korean Green Growth Trust Fund for hydropower practitioners to incorporate climate risk assessment in conjunction with environmental impact assessments. It is also noted that Tajikistan's *Medium-Term Development Programme for 2021-2025* mentions the need to approve methodologies for climate risk assessments in particular sectors as part of developing sectoral adaptation plans.

For hydropower: This will require an expanded suite of projections from multiple climate models downscaled to watershed scale, to do both an individual and a system-wide exposure and risk assessment. The downscaled projections then need to be fed into a coupled or linked modelling effort consisting of a streamflow model to account for changes in river hydrology (baseflow, peak flow, flood routing, thermal conditions and sedimentation) and then into a reservoir system management model. Some examples of modelling tools include RiverWare (a complete river–reservoir system tool incorporating hydrological processes, hydropower production and energy use, water rights and water quality) and RiverSMART, which integrates with RiverWare to explore climate change and demand scenario implications (CADSWES, 2022), or a lumped Watershed Runoff-Energy Storage model (Kao et al., 2016). Data and modelling tools are also available through the Central Asian Water (CAWa) network.

Wind, solar, storage and TPP infrastructure: Design and operation of these types of generation infrastructure need to account for the greater frequency and intensity of extreme heat events, overall warmer days and nights, and increased likelihood of more frequent and intense storms with strong winds, hail and extreme rainfall. As with hydropower, planning for climate risks in these other types of generation infrastructure entails using downscaled projections and using this information as inputs to performance and financial model tools for wind and solar, such as the System Advisor Model (Blair et al., 2018).

Transmission and distribution: Multiple subnational to regional transmission and distribution network projects are under way. They can help reduce the incidence of brownouts and blackouts through load sharing when there is stress on the energy system in one location, but spatially widespread heatwaves or extreme wind events associated with a regional storm, in addition to higher multi-country demand, can propagate risks. Various multi-model assessments such as those described in Cohen et al. (2022), Burillo et al. (2019) or Cai et al. (2019) can assist in identifying grid system fragilities.

Recommendation 3

Continue to rehabilitate weather, river and glacier monitoring stations and increase their numbers for better observational data. National hydrometeorology agencies should join CORDEX.

Semi-quantitative and quantitative risk assessments for infrastructure planning and management require good climate, river and glacier observation data and downscaled projections from multiple climate models. The weather and river station network has declined in many of the countries since the Soviet era; in situ glacier monitoring is reduced or non-existent in some locations. The low density of observations is particularly problematic in the mountains, where monitoring of changing temperatures, precipitation, snowpack and glacial extent and river flows and water quality is patchy and insufficient to capture sub-basin-scale changes.

The ‘Central Asia Hydrometeorology Modernization Project’, through investments by the World Bank, is helping to rehabilitate weather and river stations in Tajikistan and the Kyrgyz Republic, and increase the capacities of the national hydrometeorology agencies. While rehabilitation is extremely important, it is also necessary to increase the number of weather, river and glacier monitoring stations, particularly in the mountains, to capture changes in the headwaters and mid-reaches of rivers. First Central Asian Water (CAWa) and now Green Central Asia (CAWa-Green) have been expanding the network of remotely operated stations in a multi-country effort, and data are available through a public online database (Schöne et al., 2019). Large-scale modernisation of the observation network is also under way in Uzbekistan, with the support of the World Bank and UNDP. Sixty automated meteorological stations have been installed, and another 25 are planned.

In addition to improving observation data, the number of high-resolution (50 km or less) regional climate model projections is limited for Central Asia as a whole. CORDEX is one of the largest collaborative efforts of the international climate community, feeding into the IPCC Assessments, to run high-resolution RCM-GCM combinations to evaluate the performance of climate models over particular regions and produce climate projections of high-enough resolution to be used in climate risk and adaptation assessments (Giorgi et al., 2009). To date, the participation of Central Asian hydrometeorological agencies in CORDEX has been limited. Only a small number of model runs have been conducted by climate modelling institutes in Europe, Pakistan and Turkey. Because of this, the performance of only a limited number of GCMs or RCMs has been tested over Central Asia, and a more robust range of potential climate change simulations does not exist. CORDEX is reported to have contacted several national hydrometeorological agencies in 2021 and is seeking stronger engagement and collaboration with regional modellers to bring the number of models for the domain up to par with what is available for other regions.

Recommendation 4

Consider cost-effectiveness, robustness and co-benefits of potential energy infrastructure over the short and long term, with the costs of climate change and failure to adopt robust infrastructure factored in.

Ministries of energy should consider the short- and long-term cost-effectiveness, robustness and redundancy of potential energy infrastructure. They should, therefore, consider Investing in newer technologies, which are starting to be available on the market, for more robust infrastructure that is better able to withstand some changes in the frequency and intensity of extreme events and might make more economic sense in avoided damages and financial losses over the longer term. For instance, General Electric is working with Masdar to improve air flow-through in wind turbines to reduce the impacts of extreme heat on commercial-scale wind. Air-cooled, low-water-use cooling or closed-loop systems for TPPs can reduce risks associated with higher temperatures and drought. Other functional adaptation adjustments can be made to HPPs, such as increasing spillway capacities and installing labyrinth weirs to route flooding. Enhancing the glass plating of solar PV to withstand hail or implementing low- to no-water technologies available for cleaning panels are two possible adaptation options for solar parks.

Recommendation 5

Increase diversification of generation types, and strengthen transmission and distribution grids, but consider where they are built, to reduce exposure and transmission losses.

Energy infrastructure resilience will require a number of adjustments to meet dynamic and uncertain futures. Two important components of resilience are diversification of energy generation type and building in flexibility within subnational to regional networks to accommodate additional renewables likely to be built over the next 40 or so years. Installed capacity will have to increase to meet changing demand profiles as global technological innovations alter economies. Activities such as cryptocurrency mining or other IT activities may require electricity at different times and compete with agriculture and more established industry. Diversification of generation types and flexibility within the generation and transmission system as a whole to balance variable and increasing demands are needed.

Managing exposures and reducing transmission losses should be jointly considered when deciding where to build new generation capacity and place transmission and distribution lines. New generation should be installed closer to where electricity will be consumed – either major population centres or more centrally located in rural areas. The flood and water availability risks under climate change need to be considered. It does not make sense to build in an existing or likely floodplain or where there is not enough water to support operational requirements.

Recommendation 6

Join the ADB's CAREC Disaster Risk Transfer Facility to reduce financial risks while enhancing regional collaboration on climate and all-hazards risk management.

The Central Asian regional water–energy system is exposed to an increasing frequency and intensity of climate hazards over large areas, with the potential for cascading national and regional socioeconomic impacts. Existing and new energy infrastructure coming online will suffer a degree of damage and possible inoperability despite resilience measures. The protection gap – the proportion of economic losses resulting from a disaster that are not covered by insurance – is high across the three countries. Average annual losses from floods are $396 million in Uzbekistan, $395 million in Tajikistan and $73.3 million in Kyrgyzstan (TA-9878 REG, 2021a; 2021b; 2021c). Average annual earthquake losses are also substantial. Private insurance coverage is low, and governments assume most of the losses (ibid.). No regional insurance pool exists yet, although ADB has been prototyping a Disaster Risk Transfer Facility in the Central Asia Regional Economic Cooperation Region (CAREC). It is recommended that national governments participate to better manage financial risks while enhancing regional collaboration on climate and multi-hazard risk management.

Recommendation 7

Continue to strengthen efficiency efforts to reduce energy and water demand and use both within country and in coordination with regional partners.

Finally, continuing to strengthen efforts around energy and water consumption efficiencies will reduce climate risks in the energy–water system. The governments of the three countries in this study have made commitments to both mitigation and adaptation and have prioritised increasing efficiencies and reducing losses. All three are undertaking small- to large-scale efficiency improvement projects with ADB, Aga Khan, the United States Agency for International Development, UNDP and the World Bank, among other international actors. Additionally, coordination efforts around improving efficiencies in energy and water usage need to be enhanced between all countries connected through regional transmission networks. Lower efficiency ambitions and levels of implementation in one country can reduce the effectiveness of other countries' actions and prove a source of risk to all.

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Appendix 1 Methodology

Historical climate observations in the Kyrgyz Republic, Tajikistan and Uzbekistan are limited due to low weather station density and variable recording of data; data availability declined further in the 1990s in some countries after the Soviet era. The low station density is particularly problematic in catching trends in precipitation and temperature in the Pamir and Tian Shan at the basin level, as localised climates and climate trends can vary greatly with elevation and windward or leeward orientation.

Topographies influence when and how precipitation falls. When combined with temperature differences at different elevations, this influences the types of hazards that could pose risks to energy infrastructure and water security as the three countries transition their economies in a changing world. At higher elevations, rain-on-snow events can trigger flooding and mud flows along rivers in the valley areas. Snowfall accumulation and water storage in the montane glaciers and snow fields are critical for water supply and reservoir management, including for hydropower, flood management and irrigation.

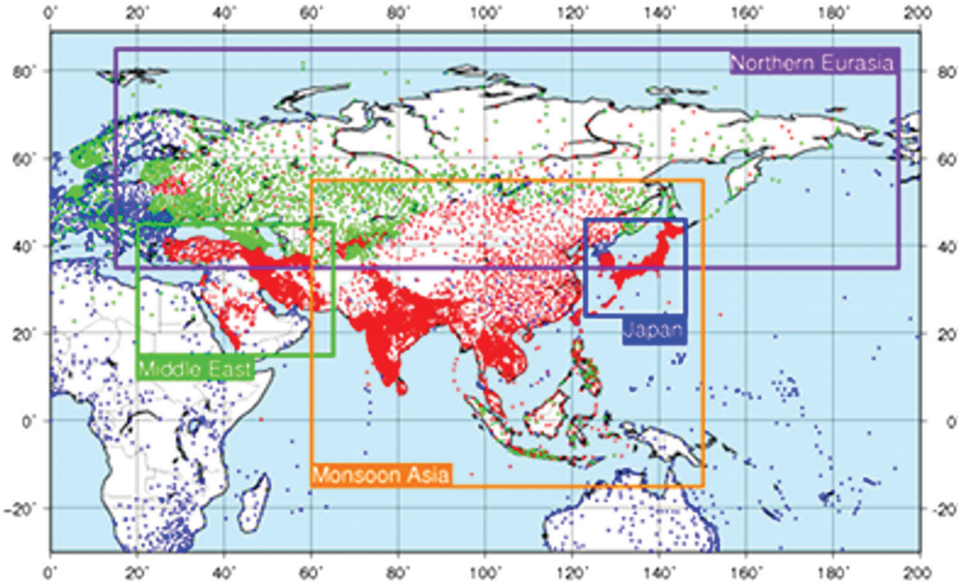
Projecting how precipitation and temperature could change on a seasonal basis, and the intensity and frequency of extremes such as heavy rainfall, heatwaves or drought requires sufficient historical climate data. Given deficiencies in station data, this project used gridded historical climate data – the APHRODITE dataset.

APHRODITE is a 50+-year gridded daily dataset covering Monsoon Asia, Central and East Asia, the Middle East and parts of Russia at a grid resolution of 0.25° x 0.25° – or approximately 25 km per grid at the latitudes of the study domain. The APHRODITE dataset remains the only long-term (since 1951) high-resolution precipitation and temperature dataset for Asia. It contains more valid stations for the continent than any other available gridded climate datasets, due to the cooperative agreements with national agencies to secure data.

For the Monsoon Asia domain, encompassing Tajikistan, the dataset covers the period 1951–2015. For all other project countries, APHRODITE data are available for the period 1951–2007. As this is a multi-country study, a baseline historical period for the precipitation data of 1971–2000 is used. While country studies indicate a climate change signal is already detectable over this period, warming rates have accelerated since 2000. Using this baseline reduces the accelerated signal's impact on the bias correction of the climate projections.

Central Asia-specific high-resolution gridded daily minimum and maximum 2-metre air temperature datasets are not as readily available. Many of the global climate modelling initiatives employ either 0.25° x 0.25° ERA-Interim (Dee et al., 2011) or 0.5° x 0.5° CRU (Harris et al., 2020) for model validation. ERA-Interim and its successors are global reanalysis data products. The typical baseline period for ERA-Interim data used in climate modelling initiatives is 1981–2005, and we used this baseline for the temperature data.

Figure 10 APHRODITE weather stations



Source: http://aphrodite.st.hirosaki-u.ac.jp/products.html

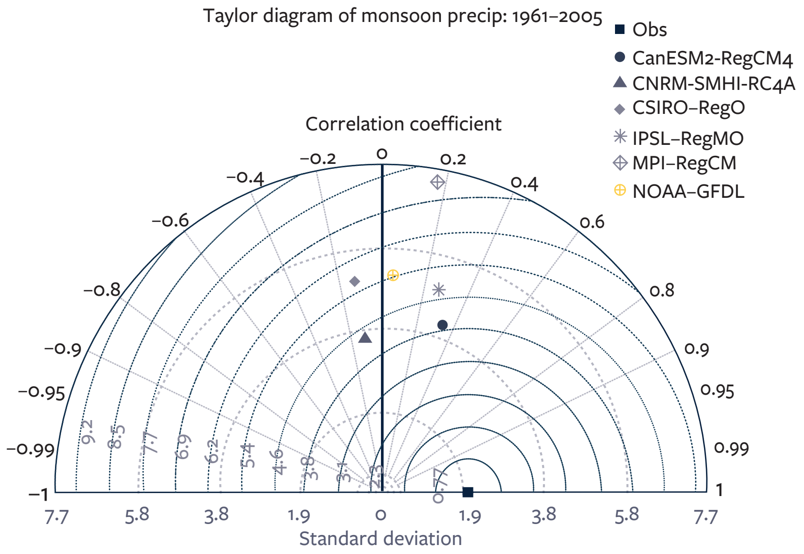
It would have been ideal to bias-correct the APHRODITE and ERA-Interim datasets against station data. However, only three months were allocated for this study, and there was insufficient time to secure the data from the national hydrometeorological agencies and process them.

Regional climate model-global climate model (RCM-GCM) simulations from the CORDEX Central Asia domain were used to examine climate change impacts on precipitation and temperature. CORDEX is a World Meteorological Organization initiative bringing together regional climate modelling and statistical downscaling to provide higher-resolution projections than is possible through the 100–500km resolution of CMIP5 or CMIP6 global climate models. Additional advantages of RCMs over GCMs include better representation of regional-to-local scale forcings, and projections of a resolution more amenable to use in climate risk and adaptation assessments and planning (Giorgi et al., 2009).

Two RCPs (2.6 and 4.5) were used. RCP4.5 is an intermediate emissions scenario; it is essentially a business-as-usual scenario and roughly corresponds to Shared Socioeconomic Pathway (SSP) 2–4.5 at 2100. RCP2.6 is a lower-emissions scenario, roughly corresponding to SSP1–2.6 at 2100; it equates to mean global temperatures staying below 2.0°C and emissions decreases after 2050. We chose RCP2.6 over RCP8.5 to demonstrate the potential risks to infrastructure even if mean global warming comes close to Paris Agreement targets.

While RCMs are able to simulate localised climate features much better than GCMs, they still often have significant biases – too much/little precipitation at the wrong times of year or locations; too hot or too cold; and so forth. Precipitation biases in historical simulations might be quite large for precipitation extremes (Kjellstrom et al., 2010); these biases may get carried forward into future projections and even be further inflated (Figure 11 summarises key biases for the monsoon region of Pakistan). Due to these biases, it is not advised that RCM projection data be directly used

Figure 11 Taylor diagram



Note: Taylor diagram comparing the performance of CORDEX South Asian models over the historical period with the APHRODITE observations for area-averaged daily precipitation over north-central Pakistan (30.625-37.12N and 69.125-75.625E) The six models have low correlations with observed daily rainfall in the July–September period for 1961–2005. The models' centred root-mean-square (RMS) error is large, indicating a wet bias ranging from ~3.8mm/day to 7.5 mm/day. All models also overestimate standard deviation, with two (CanESM2-RegCM4 and CNRM-SMHI-RC4A) nearly doubling it; all other models perform even worse in this statistic.

Source: Author analysis for RA-7989-REG.

for climate change impact assessment studies (Christensen et al., 2008), such as for future flood model estimation. RCM data need to be bias-corrected before use.

A number of bias correction methods exist. For this study, we employed a quantile mapping technique. Quantile mapping involves developing a transfer function comparing the distributions of the observed historical data with modelled historical simulations, and transforming the distribution of the modelled variable to match the distribution of the historical (Dosio and Parauolo, 2011). The transfer function is generally described as (Gudmundsson et al., 2012):

$$P_o = F_o^{-1}(F_m(P_m))$$

where P_o is the observed variable, P_m is the modelled variable, F_m is the CDF of the modelled variable, and F_o^{-1} is the inverse CDF of the observed variable.

This transfer function is then applied to future model projections (Li et al., 2010). However, RCM biases might not be stationary. That is, biases over the historical period might not persist in exactly the same way in the future. At the same time, it is likely that the real climate change signal may shift a variable's CDF in the future. A method, quantile delta mapping, corrects biases from the historical period while preserving future projected relative changes in variable quantiles (Cannon et al., 2015). In this method, the relative change is found as:

$$\Delta_m(t) = \frac{x_{m,p}(t)}{F_{m,h}^{-1}\left(F_{m \cdot p}^{(t)}\left(x_{m,p}(t)\right)\right)}$$

where the subscript *p* refers to the future projection value at time (*t*), and the subscript *h* refers to the modelled historical simulations. The bias corrected future projections are then found by multiplying the relative change function with the historical modelled bias corrected value:

$$\hat{x}_{m,p}(t) = x_{\widehat{o:m,h:p}}(t)\Delta_m(t)$$

CORDEX precipitation projections were bias-corrected against APHRODITE data, before precipitation analysis of how conditions could shift by the 2050s (2036–2065). CORDEX daily maximum and minimum temperatures for the 2050s (2041–2065) were bias-corrected against ERA-Interim data.

The multi-model mean bias-corrected projection was then used to examine yearly and seasonal changes under RCP2.6 and RCP4.5, and analysis conducted around how heavy rainfall events and heatwaves might change. Historical trend analysis was triangulated against National Adaptation Plans, country risk assessments and academic literature. The projection analysis will also be triangulated against multiple sources.