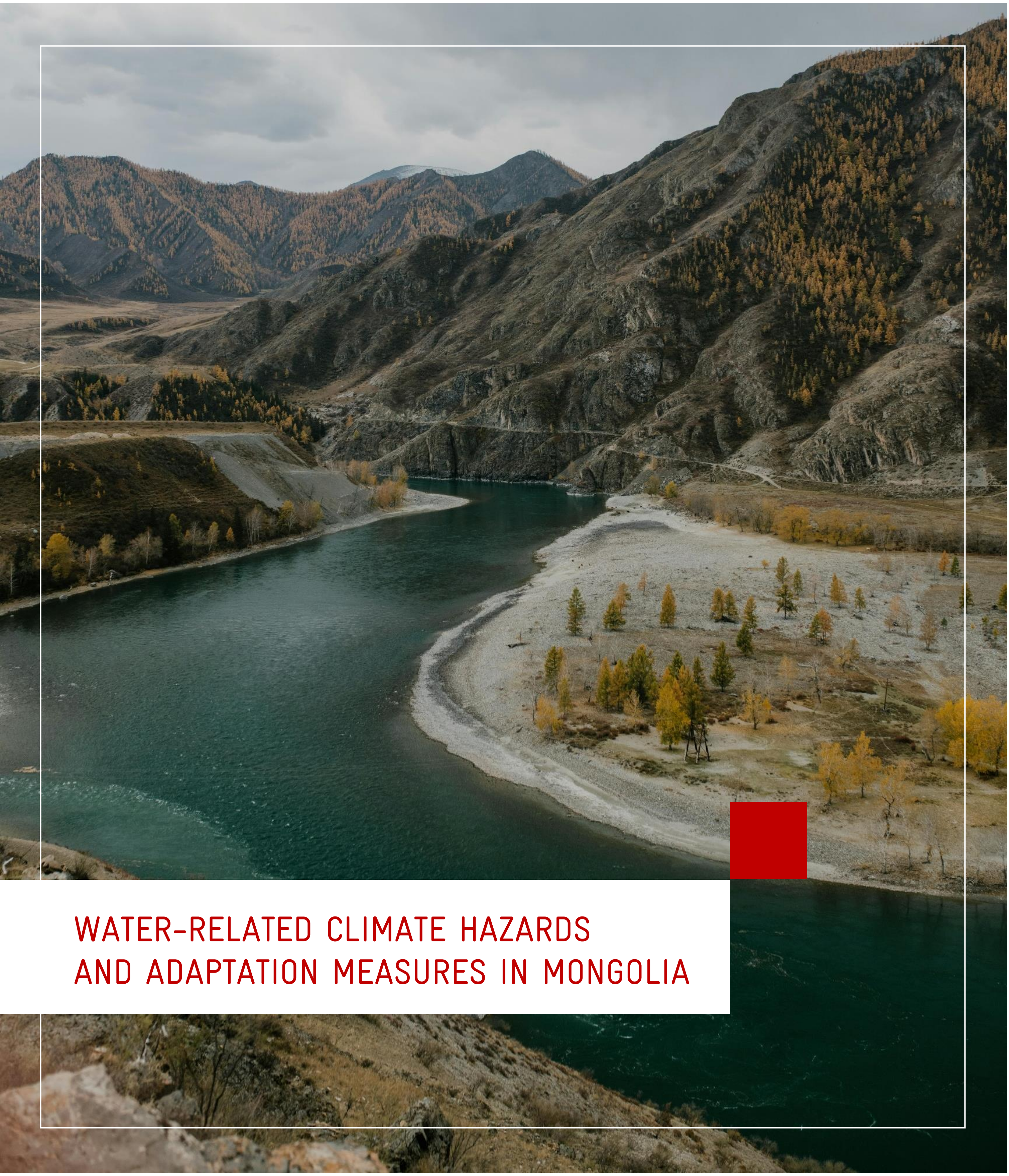

WATER-RELATED CLIMATE HAZARDS AND ADAPTATION MEASURES IN MONGOLIA

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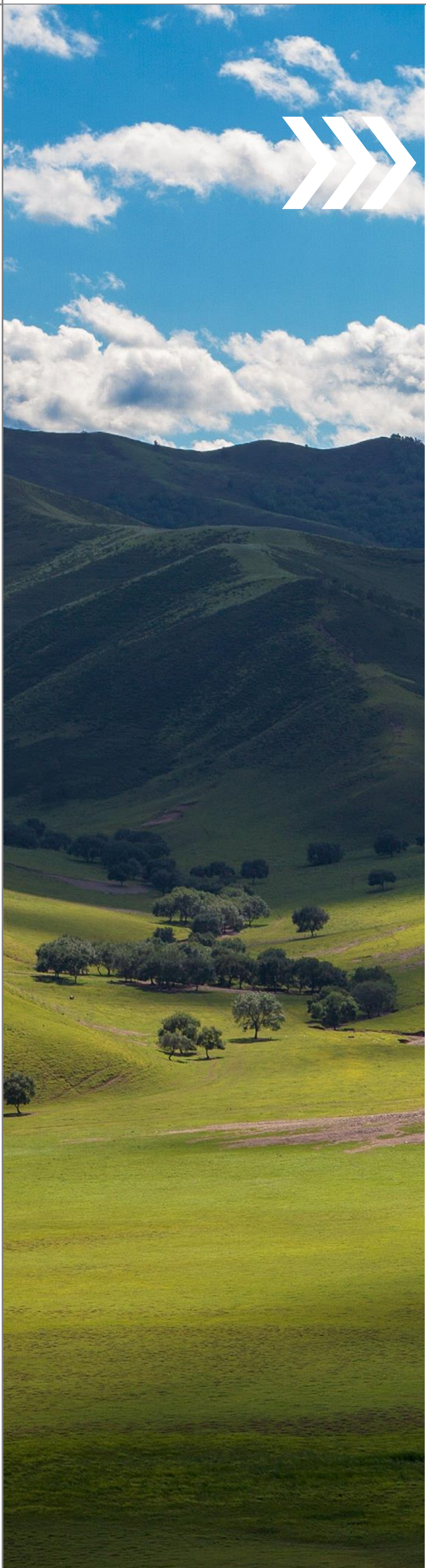
The contents of this report are the sole responsibility of the authors and can in no way reflect the official opinion of the GIZ project.

On behalf of
Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV)

Germany 2025



WATER-RELATED CLIMATE HAZARDS AND ADAPTATION MEASURES IN MONGOLIA

▶ DATA AND LITERATURE ANALYSIS

EARTH YIELD ADVISORIES

Prepared by EarthYield Advisories GbR as part of the assignment "Development of climate change related water risk assessments for Georgia, Kazakhstan, and Mongolia"

Acknowledgement

This report was prepared as part of the assignment "Development of climate change related water risk assessments for Georgia, Kazakhstan, and Mongolia" delivered by EarthYield Advisories GbR Franziska Brundell and Sophia Lüttringhaus for GIZ. Additionally, we thank our cooperation partners for this assignment for their valuable inputs and guidance: Anastasia Lobanova and Christoph Gornott.

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*Source: Illustration by EarthYield Advisories GbR

Abbreviations

Abbreviation	Description
ADB	Asian Development Bank
BMUV	Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection
CCKP	Climate Change Knowledge Portal
CDS	Copernicus Data Climate Store
CMIP	Coupled Model Intercomparison Project
CRED	Policy Advice for Climate-Resilient Economic Development
DIAPOL-CE	Policy Dialogue and Knowledge Management on Climate Protection Strategies
ESM	Earth System Model
GDP	Gross Domestic Product
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GLOFs	Glacial Lake Outburst Floods
IKI	International Climate Initiative
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
MRI	Meteorological Research Institute
NDCs	Nationally Determined Contributions
NEMA	Mongolia's National Emergency Management Agency
PET	Potential Evapotranspiration
RCP	Representative Concentration Pathway
SPEI	Standardized Precipitation Evapotranspiration Index
SSP	Shared Socioeconomic Pathways
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations International Children's Emergency Fund
WMO	World Meteorological Organization
WRI	World Resources Institute

Purpose of the assignment

The Global Programme on Policy Dialogue and Knowledge Management on Climate Protection Strategies (DIAPOL-CE) by GIZ tasked EarthYield Advisories with assessing water-related climate hazards, calculated based on the two most important variables for climate change analysis - precipitation and temperature -, in Mongolia and identifying potential adaptation measures. The project was divided into several key tasks: identifying water-related climate hazards in Mongolia, selecting the most pressing hazards, modelling the development of these hazards under different climate scenarios until 2100, identifying responsive adaptation measures, and evaluating the data findings. The primary aim of this project is to inform policymakers about potential risks and their likelihood, enabling informed decision-making regarding climate change policies in Mongolia. The core objective of the assignment, carried out by EarthYield Advisories and presented in this report, is to integrate water-related risks into macroeconomic assessments in Mongolia and policy advice, ensuring climate-resilient economic planning.

The structure of this report is designed to provide a comprehensive understanding of the water-related risks in Mongolia and the necessary measures for adaptation. The report begins with an introductory section on the water-related risks facing Mongolia, highlighting the impacts of climate change on hydrological systems, and emphasizing the importance of further knowledge regarding water-related risks. This is followed by a detailed "Background" section, which includes sub-sections on the geography and hydrology (2.1), climate and climate change (2.2) and economy (2.3) of the country. The third chapter describes the methodology of the data collection, manipulation and modelling to assess the water related risks. The fourth chapter presents results from the literature analysis and describes the water-related hazards specific to the country, providing more details for the hazards droughts (4.1), floods (4.2), heatwaves (4.3) and coastal hazards (4.4). The results of the data analysis and modelling are presented in the fifth chapter, economic damages are described in chapter 6 and adaptation measures in chapter 7. The report ends with a conclusion.

1. INTRODUCTION

Water is a fundamental resource for sustaining livelihoods and ecosystems. It further is the backbone of overall socio-economic stability and key economic sectors, including agriculture, industry, and energy production in Mongolia. Climate change significantly impacts water resources both worldwide and in Mongolia, leading to various risks including a change of precipitation patterns, an increase in frequency and severity of extreme events such as droughts or floods, a degradation of water quality and a lack of freshwater availability (Caretta et al., 2022).

In response to these growing challenges, EarthYield Advisories GbR is supporting GIZ to assess water-related risks and adaptation measures to reduce these risks in Mongolia and other partner countries. The assignment involves providing GIZ with data and information on water related risks, in particular droughts and and floods as well as heatwaves. These efforts are framed within the broader context of GIZ's global programme "Policy Advice for Climate-Resilient Economic Development" (CRED) and the project "Policy Dialogue and Knowledge Management on Climate Protection Strategies" (DIAPOL-CE), both implemented under the International Climate Initiative (IKI) on behalf of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV).

DIAPOL-CE in Mongolia includes initiatives for sustainable pasture management, water conservation efforts, sustainable livestock management, disaster risk reduction, ecosystem restoration, and contributions to Mongolia's Nationally Determined Contributions (NDCs). Additionally, there is close collaboration with Mongolia's Ministry of Environment and Tourism.

To address these challenges, our assignment includes the identification and modelling of the most critical water hazards and temperature hazards in Mongolia. We project future scenarios under different climatic conditions. These projections serve as an input to the e3.ge model, enabling a detailed understanding of potential impacts. Further our compilation and analysis of possible adaptation measures can serve to enhance the resilience of multiple economic sectors with respect to water risks. The lessons learned from these processes will support the replication of water-risk assessments across other regions, building resilience and adapting to climate change's multifaceted impacts.

Mongolia faces significant water-related risks, which are further exacerbated by climate change. The potential impacts of climate change on hydrological and geological systems in Mongolia can result in escalating damages and heightened risks to economic activities, assets, and livelihoods. Prolonged droughts, unpredictable rainfall patterns, and increased water scarcity pose severe threats to agricultural productivity, livestock management, and local communities. Additionally, the intensification of extreme weather events, such as floods, leads to further economic losses, disrupting infrastructure and livelihoods.

Mongolia's agriculture is largely dependent on reliable water availability. Reduced water accessibility could impact livestock herding and crop production in regions like Selenge and Tuv, which are crucial to the country's food security and economy. Water degradation in Mongolia might affect drinking water availability and local water supplies.

Additionally, harsh winter conditions known as Dzud can cause massive livestock deaths if the

Dzud follow droughts during the planting season. Droughts during the vegetative phase result in a lack of summer fodder and hence the demand for fodder cannot be met during winter times. This example shows the intrisicate relation between the availability of water resources, livelihoods and economic activities.

Therefore, it is necessary to mitigate these water-related risks by e.g. updating the integrated water resource management plan of the Tuul river. A first step to adaptation is an assessment of water risks.

2. BACKGROUND ON MONGOLIA

2.1. Geography and hydrology

Mongolia, located in East and Central Asia, is a landlocked nation bordered by China to the south and Russia to the north. It encompasses a vast and diverse landscape that includes steppe grasslands, the Gobi Desert, and several notable mountain ranges such as the Altai, Khangai, and Khentii (Doljin & Yembuu, 2021; Lemenkova, 2021). These mountains are part of the Central Asian Orogenic Belt, formed by complex tectonic activity, which contributed to the diverse geological structures found across the country. The Altai Mountains, for example, are notable for their rugged terrain and glacial influences. Mongolia's high mountain regions contain glaciers, being an important hydrological feature for the country. Glaciers provide the rivers with water due to the melting of glaciers and snow.

Each of these geographic features contributes to the country's unique topography.

The northern regions of Mongolia are characterized by permafrost forests (Dashtseren 2021) known as taiga, which present a stark contrast to the arid expanses of the Gobi Desert in the south. Central Mongolia features extensive grasslands that support traditional nomadic herding, while the western part of the country is dominated by the rugged Altai Mountains, known for their peaks and alpine landscapes (Lemenkova, 2021).

Mongolia's diverse terrain is further enriched by its numerous rivers and lakes, including the Kherlen, Orkhon, Selenge, and Tuul River basin, which play a vital role in the country's ecosystem and basis for economic activity. Most of the country's numerous rivers are small and ephemeral, yet the main rivers account for more than ½ of the country's total surface water flow. Lake Khuvsgul, one of the largest freshwater lakes in Asia, is often referred to as the "Blue Pearl of Mongolia" and is a key natural resource. The presence of both ephemeral and permanent water bodies shapes the geography, especially in semi-arid regions.

Despite its expansive land area, Mongolia is the world's least densely populated country, offering vast open spaces. The combination of high altitude and continental climate results in significant temperature variations, contributing to the country's unique environmental challenges.

2.2. Climate and climate change

Mongolia's climate is characterized by extreme continental conditions, with long, harsh winters and short, hot summers. The country experiences significant temperature variations due to its high altitude and continental climate (World Bank and ADB, 2021). Mongolia receives relatively little precipitation, averaging between 200-350mm annually, contributing to arid conditions in regions like the Gobi Desert (UNDP 2023; World Bank and ADB, 2021). The combination of Mongolia's high altitude and continental climate leads to extreme temperature fluctuations, impacting both human and ecological systems. Climate change is expected to exacerbate these variations, intensifying challenges such as water scarcity, particularly in central and southern Mongolia (Doljin & Yembuu, 2021)

Over the past decades, Mongolia has faced increasing climate change impacts. Global warming changed and will continue to change the following in the country: temperature increase, precipitation changes, water scarcity, drought, groundwater depletion, urban water challenges, ecosystem impacts, as well as impacts on the overall economy and livehoods. The country has experienced a temperature rise of over 2°C between 1940 and 2015, a rate higher than the global average (World Bank and ADB, 2021). Projections suggest Mongolia could see an increase of 3°C to 5°C by the end of the century under high emission scenarios (World Bank and ADB, 2021). This warming trend is particularly affecting daily maximum and minimum temperatures. As a result of these changes, extreme weather events such as heatwaves, droughts, and riverine flooding are becoming more frequent and intense (World Bank and ADB, 2021).

The phenomenon known as "Dzud," a harsh winter following a dry summer that causes significant livestock losses, has also become more severe and frequent (UNDP 2023). Desertification poses another significant threat to Mongolia, particularly in the Gobi Desert (Doljin & Yembuu, 2021). Rising temperatures lead to soil drying, vegetation loss, and erosion, while melting permafrost destabilizes soil structures (World Bank and ADB, 2021).

The IPCC's Sixth Assessment Report highlights that such changes in arid and semi-arid regions can lead to increased land degradation and desertification (IPCC, 2022).

Unpredictable precipitation patterns exacerbate these issues, leading to prolonged droughts and intensified erosion from heavy rains (World Bank and ADB, 2021). The degradation of grasslands and expansion of desert areas result in shrinking pasturelands, water scarcity, and a loss of biodiversity (UNDP 2023, World Bank and ADB 2021). This creates a feedback loop that further intensifies the effects of climate change in the region (IPCC, 2022).

These climate-driven changes have significant impacts on Mongolia's ecosystems and pastoral livelihoods. Recent data shows that the 2023-2024 Dzud affected 90% of Mongolia's territory, resulting in the loss of more than 7.4 million livestock, or about 11% of the total livestock population according to the National Emergency Management Agency (NEMA).

2.3. Economy

Mongolia's economy is a blend of modern and traditional sectors, heavily reliant on natural resources and influenced by neighbouring China and Russia. Key sectors include mining (coal, copper, gold, uranium), which contributes 20-30% to the Gross Domestic Product and up to 89% of annual exports (World Bank and ADB, 2021), and agriculture (livestock herding and cashmere production), which is highly vulnerable to climate change. Climate change threatens these sectors. For example, mining is a water-intensive industry suffering from both water scarcity and also extreme events such as floods as it damages infrastructure. Livestock herding is threatened by reduced pasture quality, increased mortality rate, water scarcity and desertification exacerbated by climate change. And crop production faces increased droughts affecting soil fertility and hence productivity, extreme events affecting crop yields and shortened growing seasons due to climate change.

The service sector is growing in the capital region. The economy faces challenges such as underdeveloped infrastructure, lack of diversification (heavy reliance on minerals), landlocked location of the country and poverty in herding communities. Despite slow foreign investment due to regulatory hurdles, Mongolia is one of the fastest-growing yet volatile economies, with significant potential for wind and solar energy.

3. METHODOLOGY • Data collection, manipulation and analysis

The methodology followed a precise succession to ensure transparency and replicability of all necessary steps,

- Literature analysis and expert exchange to identify most important hazards and further country-specific information
- Identification of data requirements and model assumptions
- Data retrieval through trial and error
- Selection of a suitable data source
- Data download
- Identification of hazard classifications
- Preparation of data for each hazard
- Calculation of probability of occurrence for each classification

3.1. Literature analysis and expert exchange

As an initial step, this study analysed both scientific and grey literature i.e. peer-reviewed papers and reports issued by international organizations, such as reports white papers or conference papers, as well as documents provided by GIZ to gain both an insight into the scientific status quo and to isolate current trends and challenges as well as to identify the most pressing water-related hazards in relation to climate change in the relevant country. The analysis also aimed to analyse specific policy frameworks and guidelines relevant to each country. Lastly, the literature analysis provided an initial search of appropriate data and data frameworks to establish which climate models could be used and which scenarios could be appropriately depicted. This included data sets from Copernicus, the Aqueduct Water Risk Atlas by the World Resources Institute, the World Bank Climate Change Knowledge Portal. The scientific literature was identified through systematic searches and grey literature was gathered from institutional repositories, government websites, and relevant international organizations. The initial focus was the identification of hazards and risks, searched with the keywords "climate change hazards Mongolia", "hydrology Mongolia", "water risks Mongolia" and "climate change water hazards Mongolia". Additionally, the most commonly used reports were analysed, including the sixth IPCC report, documents of the World Bank Climate Change Portal and the Climate Risk Country Profiles by the Asian Development Bank. Lastly, documents provided by GIZ, including internal reports, country-specific data, and project evaluations, served as a crucial source of context-specific information.

Correspondingly, expert talks from all country packages assisted in the identification of the most pressing water-related hazards that all countries have in common, the most vulnerable sectors in Mongolia and the guidelines on possible adaptation measures. These talks were held in regular intervals with relevant stakeholders and economists for Mongolia.

3.2. Data analysis

The literature analysis and the expert talks as well as the requirements by the economic model, namely the necessity for annual data, data for the SSP scenarios 1-2.6, 2-4.5 and 5-8.5 and for hazards with the most severe expected economic damages, led to the identification of the water-related hazards riverine floods and meteorological droughts as well as heatwaves. Other important water hazards such as general floods, hydrological droughts and general water depletion had to be abandoned due to a lack of available data. In the entire study data constraints were of importance, as the data situation is not fully established in Mongolia, the preceding project focused on different hazards and the data used had to be preferably open-source and easily accessible to be considered.

The data and the hazard model had to fit the following criteria to be taken into consideration:

- Simulation of future values and interpretation of historical values for variables that are relevant to heatwaves, meteorological droughts and riverine floods.
- Differentiation of spatial grids with sufficient spatial resolution, i.e. grids that do not only show one value per country.
- Daily or monthly values that can be calculated into an annual probability of occurrence of three different hazard classifications.
- Establishment of three hazard classifications: low hazard, medium hazard, high hazard.
- Future projections from 2024-2080 or longer.
- Provision of annual projections.
- Possible recreation of data manipulation by future policymakers using open-source data and easily replicable workflows.
- Full projections for the following scenarios
    - Shared Socioeconomic Pathways (SSP) 1- Representative Concentration Pathway (RCP) 2.6 (Sustainability – Low Emissions, Paris Agreement),
    - SSP 2- RCP 4.5 (Middle of the Road – Intermediate Emissions), and
    - SSP 5- RCP 8.5 (Fossil-fueled Development – High Emissions).

3.2.1. Data sources

Data sources for Mongolia include ISIMIP, Copernicus Climate Data Store, CMIP6, NASA EarthData, the World Bank Climate Change Portal and the Aqueduct Water Atlas by the World Resources Institute. They differ in how the data is presented (manipulated data vs raw data), resolution, temporal differentiation and RCD/SSP scenarios available. Constraints of the project included a specific timeframe, pre-selected SSP scenarios, the integration into the economic model and time available.

The initial workplan of this assignment aimed for the use of the Aqueduct data repository with pre-existing projections of drought and floods and its corresponding Water Atlas. Unfortunately, the data was only available in 30-year intervals, making it impossible to calculate accurate estimations of the probability of occurrence for each year in the economic model, Similarly, the Climate Change Knowledge Portal (CCKP), which also provides pre-manipulated data, had to be excluded as the variables were only available for the country as a whole and were already aggregated Yet, both sources can be used as excellent reference points for verification and initial trends.

The study's objective was to fully work with unprocessed data from a widely used international climate model.

The selected model was the Meteorological Research Institute Earth System Model version 2 (MRI-ESM2-0), developed by Japan's Meteorological Research Institute (MRI) (Yukimoto et al., 2019). This model is part of the Coupled Model Intercomparison Project (CMIP6), a global initiative for climate projections under different future scenarios. MRI-ESM2-0 includes advanced simulations of atmospheric, oceanic, and land processes, making it particularly suitable for studying regional climate patterns in Central and Western Asia, including Kazakhstan, Mongolia, and Georgia.

This model was chosen for its ability to accurately represent mid-latitude weather patterns and capture variations in temperature and precipitation in continental and semi-arid climates. Such capabilities make it a valuable tool for assessing the potential impacts of climate change on agriculture, water resources, and ecosystems in these regions. Additionally, many other models had to be excluded due to limited data availability or missing scenario projections

MRI-ESM2-0 has a spatial resolution of approximately 110 km × 110 km. The historical baseline used for analysis is 1981–2010. Although baselines from 1991–2020 are now more commonly used, this was not an option for MRI-ESM2-0, as its available data only extends to 2014. The 1981–2010 baseline was chosen because it provides both climatic relevance and a sufficiently large dataset for analysis.

The data was retrieved from Copernicus Data Climate Store (CDS)1. The CDS provides free and open access to climate data, offers a comprehensive climate data collection, has a user-friendly interface and provides access to a variety of CMIP6 climate projections, which were published in 2021. Furthermore, the CDS is regularly updated and can be tailored for different applications. Lastly, the ability to apply spatial and temporal filters to data requests made the downloading process more efficient. Lastly, the option exists to apply spatial and temporal subsets to data requests, which made it more efficient in downloading the required data.

The original project scope required that the data had already been cleared for bias and manipulated for further research (such as with Aqueduct and CCKP) and that no programming skills are required. This, however, proved impossible if also taking spatial and temporal differences into account and allowing for the fact that the study aims to identify extreme events and the likelihood thereof. In order to fulfill a projection of this scope on an annual basis, both the use of international climate data and the ability to work with Python are necessary.

Therefore, the following steps were necessary to obtain the data sets for Mongolia:

a. Identification of relevant data sets due to geography and time constraints of the project.
b. Evaluation of available climate data sources.
c. Exclusion of pre-processed data sources, such as the Aqueduct Water Atlas and the CCKP, due to limitations in temporal resolution and spatial aggregation.
d. Selection of a suitable international climate model for data processing
e. Justification of the selected model based on its spatial resolution and historical baseline, which provided a balance between data availability and climatic relevance
f. Retrieval of raw data from the CDS, which was selected for its open access, extensive climate projections, user-friendly interface, and ability to apply spatial and temporal filters to streamline data downloads.
g. Acknowledgement of necessary programming skills.

3.2.2. Variables

Based on the data requirements needed to identify and analyse the three water hazards - heatwaves, droughts and riverine floods - and the restriction of available data for the respective countries, scenarios and time frame, the following variables in a 110km x 110km

[1] https://cds.climate.copernicus.eu/

resolution for the whole landmass of all three countries were chosen:

- Daily precipitation
- Monthly precipitation
- Daily mean near-surface air temperature
- Daily maximum near-surface air temperature
- Monthly mean near-surface air temperature
- Daylight hours
- Monthly total runoff
- Monthly moisture in upper portion of soil column

3.2.3. Scenarios

The project favored the more commonly used 6th generation SSP scenarios (SSP1-2.6, SSP2-RCP 4.5 and SSP5-RCP 8.5) for a seamless integration into the economic model. These SSP scenarios were chosen over earlier ones because they offer a more comprehensive framework that integrates socioeconomic conditions with climate projections. The 6th generation of climate scenarios, known as SSPs, combines socioeconomic development narratives with radiative forcing levels, providing a nuanced exploration of potential climate futures and their societal challenges. Unlike RCPs, which focus solely on greenhouse gas concentration trajectories, SSPs incorporate economic growth, population dynamics, technological advancements, and policy implementation. This integration allows SSPs to represent the interplay between socioeconomic factors and climate impacts, offering a broader context for understanding potential futures. SSPs work alongside RCPs, linking climate outcomes with realistic socioeconomic contexts, enabling researchers to explore a wider range of climate adaptation and mitigation strategies. This flexibility makes SSPs superior for studying climate risks and societal capacities to address these risks under varied development pathways, offering a holistic tool for policy-relevant climate research.

3.3. Data manipulation

The final required data from the CDS was downloaded on October 16, 2024, subsequently manipulated and the relevant indicators were modeled. The data can be accessed manually and does not require a specific program, i.e., an Application Programming Interface. It is possible to choose any sub-setting of the data, for example temporal periods or geographical locations, manually.

Following the download of the data, the programming language Python (open-access) was used to run all calculations and visualizations. In order to perform different tasks with Python, a variety of so-called Individual packages and libraries are necessary and have to be installed accordingly and as needed, the most important examples include xarray, pandas, netCDF4 and, matplotlib. Xarray was used, because it makes working with large, multi-dimensional datasets (like temperature and precipitation over time and space) much easier by using labeled dimensions. Pandas allows handling of missing values, data filtering and aggregation of data in time-series climate data. NetCDF4 is required to read data that is provided in a CDS4 file like most climate data. Matplotlib allows the user to visualizations out of climate data and was used to create graphs and maps.

All calculations and modelling presented here, can be executed and replicated with the use of open-source software, but requires programming skills and knowledge of data science.

3.4. Calculation and modelling

3.4.1. Meteorological droughts

The Standardized Precipitation Evapotranspiration Index (SPEI) was selected as the primary parameter for the drought calculations in Mongolia as it offers a comprehensive approach to assessing water balance, making it a highly effective tool for capturing drought conditions. Unlike indices that rely solely on precipitation, SPEI incorporates both precipitation and potential evapotranspiration, allowing it to account for the influence of temperature and other climatic variables on water availability. This sensitivity to multiple climate variables, especially temperature fluctuations, enhances the accuracy of drought assessment under changing climate conditions. Additionally, SPEI's multi-scalar nature is particularly valuable, as it allows for analysis over different timescales—from short-term monthly droughts to multi-year periods. This versatility makes SPEI an ideal choice for comparing drought severity across regions with differing climatic characteristics. In this study the 12-month scale was chosen, as it captures the balance between moisture input and atmospheric demand over a full annual cycle. This scale is well-suited for detecting prolonged periods of moisture deficit or surplus. Since it reflects cumulative water stress over a year, the 12-month SPEI can reveal trends and anomalies in annual hydrological balance, which are crucial for planning in water-sensitive regions and for managing long-term environmental and economic impacts of climate variability. For the calculation of the SPEI index and subsequently the probability of the occurrence of a drought, daily temperature, daily precipitation and sunlight hours were used. As a first step, potential evapotranspiration (PET) was calculated using the Thornthwaite equation, using that to calculate the water balance with the precipitation data on a monthly basis, daylight hours were required from the original data (Aschonitis et al. 2021), creating a SPEI index. The SPEI was subsequently calculated for each grid point on the map. To enhance the analysis of drought severity, we further classified each event by its SPEI score. Drought events were categorized into three hazard levels: low hazard for scores below -1, medium hazard for scores below –1.5 and high hazard for scores below –2. In order to identify the probability of occurrence for each hazard classification as well as the mean probability of occurrence for the historic baseline period, a gradient boosting regressor was run. The gradient boosting regressor method produces a continuous output that can directly be interpreted as the probability of occurrence. The project required the final presentation of the data to be in an Microsoft Excel format. As a last step, the data was thus saved as a NetCDF file and was then subset to the individual countries and exported to a CSV file.

The limitation of this approach to project droughts is the Thornthwaite equation, because other equations are more precise as they use more data formats, but this data was not available to the project.

3.4.2. Riverine floods

For the projection of riverine floods in Mongolia several variables had to be considered to fully portray the risk of riverine flooding in each country. Due to the meteorological complexity of floods, various hydrological factors such as soil porosity, vegetation, land use and steepness should be taken into consideration but are almost always impossible to do so on a large-scale basis. Further, due to the occurrence of flash floods and the necessity for real-time data, riverine floods are difficult to predict (Perrera et al 2020). Additionally, data shortages and restrictions only allowed for a specific selection of variables. The following variables were chosen and subsequently categorized into a composite risk score to project possible future riverine floods in each grid point:

- **Monthly Total Runoff**: Representing the volume of water that flows over land surfaces and into rivers after precipitation events, total runoff is an established key driver of riverine floods. Runoff levels can rise significantly due to heavy precipitation, snowfall, saturated soil conditions or persistent rainfall, which causes rivers or stream to exceed their capacity and can lead to overflow. Due to the varying nature of reasons for total runoff, this variable serves as a proxy for lacking data and is particularly useful for the assessment of riverine flooding as it integrates the effects of precipitation, land saturation, and watershed characteristics, all of which influence how quickly and intensely riverine flooding may occur (IPCC, 2014).
- **5-Day-Precipitation-Events**: Daily precipitation is not an ideal proxy for floods, as duration, intensity and overall wetness are difficult to estimate when just looking at mean precipitation in any given location. 5-day-cumulative precipitation events on the other hand show an extreme event of prolonged precipitation more than average precipitation and affect the risk of riverine flooding accordingly. Statistically, riverine floods are more likely to occur after prolonged precipitation events (EEA, 2021)
- **Number of Days with Precipitation over the 95th Percentile**: A commonly used variable in flood prediction is the variable number of days with rainfall over 50mm. This variable is not suited for the particular project regions, as they are predominantly dry and in some regional cases arid or semi-arid. The isolation of the 95th percentile in the historical baseline therefore represents extreme rainfall more adequately. Flash floods and riverine floods often occur after extreme rainfall as the event overwhelms drainage systems, saturated soils and riverbeds (Cotterill et al, 2021; Tamm et al, 2023).
- **Daily Temperature**: Surface temperature is not directly linked to flooding, but commonly used as a proxy for snowmelt and evaporation. The variable is particularly useful in mountainous regions with increased snowmelt in specific seasons, during which rivers swell to more than their normal size. Additionally, in warm regions, high temperature can reduce soil moisture and increase frequency of heavy rainfall (UNEP 2020).
- **Soil Moisture**: Soil moisture directly affects how much rainfall infiltrates the soil versus how much becomes surface runoff that flows into rivers. High soil moisture levels indicate that the ground is near saturation, meaning it has limited capacity to absorb additional rainfall, which increases the volume of runoff entering river systems. When soil is already saturated from previous precipitation or snowmelt, even moderate rainfall can lead to rapid increases in river levels, raising the likelihood of flooding (Yu et al. 2023; Ran et al. 2022).

In the composite risk score, all variables were given equal weighting with the exception of temperature, which was given more importance (50%) between January and May due to flood risk caused by snowmelt in the mountains and no importance (0%) between June and December. Following that, the risk score was calculated for the baseline and future periods. The monthly risk score was then aggregated to an annual risk score.

To enhance the analysis of flood severity, we further classified each event by its percentile in the historic baseline period. Flood events were categorized into three hazard levels: low hazard for the 80th percentile, medium hazard for the 90th percentile and high hazard for the 98th percentile. In order to identify the probability of occurrence for each hazard classification as well as the mean probability of occurrence for the historic baseline period, a gradient boosting regressor was run. The gradient boosting regressor method produces a continuous output that can directly be interpreted as the probability of occurrence. The project required the final presentation of the data to be in a Microsoft Excel format. As a last step, the data was thus saved as a NetCDF file and was then subset to the individual countries and exported to a CSV file.

Limitations of this approach include that the inclusion of a hydrological model would be beneficial but was outside the scope of this project. Hydrological models often have the ability to include land use and terrain, understand individual river dynamics and can simulate rainfall-runoff relationships. Furthermore, risk scores are model estimates rather than facts. Additionally, floods are influenced by numerous factors including local geography, land use, river flow dynamics and more, which makes them non-linear, complex phenomena that should best be studied at a more local level.

3.4.3. Heatwaves

In this study, defining heatwaves required a tailored approach due to the variability of temperature norms across the three different countries as well as across the different regions within Mongolia. A single temperature threshold is insufficient for capturing heatwave events universally, as what constitutes an extreme temperature in one region may be typical in another. To address this, we adopted the heatwave definition provided by the previous project partner University of the Balearic Islands (GIZ, 2021a), which aligns with previous research methodologies while allowing for regional climate variability. According to this definition, a heatwave occurs when daily maximum temperatures exceed the 99th percentile of historic baseline temperatures for that specific location and this elevated temperature persists for more than five consecutive days. This percentile-based approach provides a more regionally adaptable framework for identifying heatwaves by anchoring them in location-specific temperature extremes rather than a fixed absolute threshold.

Once heatwave periods were identified using this definition, we extracted these events from both historic baseline data and projected future climate data under various climate scenarios. To do this, the 99th percentile was calculated for each grid point of the data across the historical baseline period, followed by the calculation of exceedances under each SSP scenario. We then aggregated these heatwave occurrences on a monthly basis to quantify the frequency of heatwaves over time, capturing both the number of heatwaves per month and per year. This aggregation allowed us to track shifts in the seasonal and annual distribution of heatwave events, providing insights into potential changes in heatwave frequency and timing under different future climate conditions. To enhance the analysis of heatwave severity, we further classified each event by its duration. Heatwave events were categorized into three hazard levels: low hazard for events lasting for at least 5 days, medium hazard for events lasting at least 8 days, and high hazard for events persisting longer than 10 days. In order to identify the probability of occurrence for each hazard classification as well as the mean probability of occurrence for the historic baseline period, a gradient boosting regressor was run. The gradient boosting regressor method produces a continuous output that can directly be interpreted as the probability of occurrence. Compared to other methods such as a classifier it allows to capture the likelihood of an event in a given location and provides insights into areas which increasing or decreasing risk, making it suitable for identifying long-term climate trends.

The project required the final presentation of the data to be in an Microsoft Excel format. As a last step, the data was thus saved as a NetCDF file and was then subset to the individual countries and exported to a CSV file.

The limitations of this approach for heatwaves are that additional climate variables could be added, which influence heatwaves, such as humidity, soil moisture and wind speed if the data allows for it. Adding these features would help the model better capture the conditions leading to heatwaves, thereby enhancing prediction accuracy. Furthermore, combining this model with physical climate models could provide insights that are also physically interpretable in the future.

4. LITERATURE ANALYSIS • Findings

Mongolia faces significant water-related risks due to its arid environment and climatic extremes. According to the most recent AQUEDUCT water stress data, Mongolia faces high water stress now and, in the future, (WRI, 2024). According to AQUEDUCT, water stress is the ratio of total water demand to available renewable water supplies. It is an indicator of competition for water resources and is defined informally as the ratio of demand for water by human society divided by available water. At baseline the country had a water stress index of 3.13 ranked on a scale from 0 (low stress) to 5 (extremely high stress). According to the AQUEDUCT projections, water stress is aggravating in the future: 3.30 (2030), 3.72 (2050), 3.34 (2080).

Water resources are unevenly distributed across the country, with rainfall ranging from 350mm annually in the north to 80mm in the southern Gobi Desert (ADB, 2020a). While the country's overall water endowment is high per capita, regional differences in rainfall and population distribution create localized water insecurity, particularly in Ulaanbaatar and the Gobi region (ADB, 2020a). A report from 2011 highlighted that in Ulaanbaatar, 50% of the population lives in informal settlements with limited access to water, consuming only 5-10 liters per capita per day (Batimaa et al, 2011)

Groundwater is Mongolia's primary source for drinking and industrial water due to high seasonal variability and winter freezing of river flows (ADB, 2020a). In the Gobi Desert, which constitutes 30% of the country's territory, both livestock and rely heavily on groundwater (Erdenebat, 2023). The mining sector is projected to be the dominant water user by 2025, consuming an estimated 83 million cubic meters per year (Erdenebat, 2023).

Climate change is exacerbating these challenges. Mongolia's average temperature has increased by 2 degrees Celsius over the past 70 years (Dialogue Earth, 2023). Rainfall patterns have changed over the past 40 years, with intense deluges replacing previously common light rains (Dialogue Earth, 2023). This has led to an increase in flooding incidents, from 9 recorded events in 2004 to 72 in 2022, according to Mongolia's National Emergency Management Agency (NEMA).

The changing climate and water availability are impacting both rural and urban areas. In rural regions, erratic weather patterns are contributing to land degradation and livestock losses, with over 75,000 livestock lost due to flooding and heavy rain between 2004 and 2021 (Dialogue Earth, 2023). In urban areas, particularly Ulaanbaatar, rapid urbanization is straining water resources. About 60% of Ulaanbaatar's population lives in 'Ger' areas without adequate sanitation infrastructure (Excell & Moses, 2017).

Water pollution, especially from mining activities, is a growing concern. Heavy metals and toxic chemicals from gold extraction have contaminated groundwater and rivers, posing health risks to communities relying on local water sources (Excell & Moses, 2017).

These challenges are compounded by a lack of transparency in water pollution information. Despite laws mandating disclosure of environmental data, many poor communities remain uninformed about the safety of their water sources (Excell & Moses, 2017).

Addressing these issues requires a holistic approach through integrated water resources management (IWRM), as the traditional fragmented approach is insufficient to tackle the complex water challenges facing Mongolia (ADB, 2020b).

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These challenges are not unique to Mongolia but are part of broader regional trends in Central and East Asia. Central Asia experienced lower-than-usual inflows into reservoirs, putting stress on the environment, society, and economy (WMO, 2024). The region also experienced much-below-normal soil moisture and terrestrial water storage conditions (WMO, 2024). Regarding the precipitation patterns, parts of East, North, and Central Asia, including Mongolia, witnessed above-normal precipitation in 2023, but significant rainfall deficits occurred in other parts of Asia (WMO, 2024). This imbalance in precipitation patterns underscores the region's vulnerability to erratic and extreme weather patterns, complicating water management efforts (WMO, 2024). Aggregated precipitation data highlight that precipitation is a highly local event; while one part of a village may face extremes, another part may not experience it (WMO, 2024).

Another alarming fact presented in the report is the significant glacier runoff reductions expected due to climate warming, with Central Asia being one of the most affected regions (WMO, 2024). In particular, small glaciers in Central Asia are retreating rapidly (WMO, 2024). These reductions have significant effects on water basins and resources (WMO, 2024).

The changing climate and water availability are impacting both rural and urban areas. In rural regions, erratic weather patterns are contributing to land degradation and livestock losses, with over 75,000 livestock lost due to flooding and heavy rain between 2004 and 2021 (Dialogue Earth, 2023). In urban areas, particularly Ulaanbaatar, rapid urbanization is straining water resources. About 60% of Ulaanbaatar's population lives in 'Ger' areas without adequate sanitation infrastructure (Excell & Moses, 2017).

Water pollution, especially from mining activities, is a growing concern. Heavy metals and toxic chemicals from gold extraction have contaminated groundwater and rivers, posing health risks to communities relying on local water sources (Excell & Moses, 2017).

These challenges are compounded by a lack of transparency in water pollution information. Despite laws mandating disclosure of environmental data, many poor communities remain uninformed about the safety of their water sources (Excell & Moses, 2017).

Addressing these issues requires a holistic approach through integrated water resources management (IWRM), as the traditional fragmented approach is insufficient to tackle the complex water challenges facing Mongolia (ADB, 2020b). These findings emphasize the critical need for enhanced monitoring systems, data collection, and data sharing, particularly in the Global South where Asia remains underrepresented in hydrological data collection (WMO, 2024).

In the following we will focus on the four hazards droughts, floods, Dzud and desertification. This focus is driven by the profound impact these phenomena have on the region and the significant threats they pose to the environment, society, and economy. Droughts and floods are also the common denominators across the three GIZ country packages Mongolia, Georgia and Kazakhstan which are analysed. Understanding and addressing these hazards risks are crucial for several reasons:

- Droughts lead to soil moisture depletion, reduced agricultural productivity, and water scarcity.
- Floods cause damage to infrastructure, loss of life, and economic disruption.
- Both droughts and floods exacerbate rural-to-urban migration, placing additional pressure on urban resources.
- Dzuds cause severe livestock losses.
- Desertification affects vegetation and soil health, hence impacting agricultural and other economic activities.

4.1. Droughts

Droughts present significant risks to Mongolia, particularly impacting pastoralism and agriculture. The country has experienced reduced pasture quality, crop failures, water scarcity, and desertification due to prolonged dry periods. Historically, severe droughts during the 1990s and 2000s resulted in the loss of millions of livestock (with 11 million deceased animals between 1999 and 2002), leading to widespread economic hardship. In 2017, for instance, drought conditions necessitated the import of cereals to satisfy domestic demand, contributing to rising food prices and food security concerns. The economic stability of pastoralist communities remains vulnerable, as they must adapt to sudden poverty induced by these environmental changes.

International projections indicate that Mongolia will continue to face increasing drought frequency and intensity due to above-average global warming and desertification. This scenario could lead to further importation of agricultural produce, escalated food prices, and significant challenges for food security. For example, the drought in 2017 had the repercussion that cereals needed to be imported to satisfy domestic demand. Additionally, rural-to-urban migration, especially among herders and farmers, may add pressure on urban centres like Ulaanbaatar.

4.2. Floods

While less common than droughts, floods in Mongolia are becoming increasingly problematic due to changing precipitation patterns. Flood events, such as those in 2016 and 2018, have caused substantial damage to infrastructure, particularly in Ulaanbaatar, where ger districts and informal settlements are highly susceptible to flash floods. The 2018 floods resulted in widespread infrastructure damage in the capital, while the 2016 floods affected around 2000 households in the north, causing significant agricultural losses. Such events can further lead to the establishment of informal settlements and water contamination.

Projected increases in flood frequency are linked to more intense and unpredictable rainfall, a rise in heavy rainfall events, and glacial melting, which raises the risk of glacial lake outburst floods (GLOFs). These changes pose severe implications for Ulaanbaatar's infrastructure, potentially leading to frequent and costly disaster recovery efforts. Water contamination, agricultural losses, and damage to roads and bridges will further strain Mongolia's economic stability, necessitating the redirection of resources to emergency response and rehabilitation.

Overall, the increasing frequency and severity of both droughts and floods underscore the urgent need for Mongolia to implement comprehensive disaster management and climate adaptation strategies to safeguard its economic stability and livelihood of its communities.

4.3. Heatwaves

Mongolia has been experiencing a stark increase in heatwaves in the past decades and has generally experienced higher and faster rises in mean temperature and maximum temperature than the global average, with the exception of winter temperatures (GIZ, 2023). The average annual air temperature increased by 2.24°C between 1940 and 2015 (GIZ, 2023). Furthermore, soil moisture has been showing deficits due to decreased precipitation and increased surface warming, which leads to an increasingly hot climate in the country (Han et al. 2021). Furthermore, intense or prolonged heatwaves exacerbate the risk for droughts and, in turn, for desertification, which are both prominent issues in Mongolia already (Kapoor et al. 2021).

The economic impact and the consequences for human health are manifold and include livestock losses, reduced yields of wool and cashmere, a deterioration of respiratory diseases in the population, an increase in tick-borne diseases and an increased risk for wildfires (Kapoor et al. 2021).

Both the magnitude and frequency of extreme heat events is projected to increase in Mongolia, which is further supported by the data findings of this report. Heatwaves are projected to increase under all Representative Concentration Pathway (RCP) climate scenarios (GIZ, 2023).

4.4. Dzud

Dzuds are severe winter disasters that pose a significant threat to Mongolia's pastoral economy and livestock. These extreme weather events, characterized by harsh winter conditions, i.e. heavy snowfall, severe cold, and limited access to pasture, following summer droughts. Dzuds can lead to widespread livestock mortality, economic slowdown, internal migration and other impacts (Surenkhuu & Boldbaatar, 2022, Roeckert & Kraehnert, 2022). There are several types of Dzuds, including white (heavy snow), black (lack of snow), iron (ice crust), cold (extreme temperatures), and combined Dzuds (Surenkhuu & Boldbaatar, 2022.

Dzuds occur on average once every 4-5 years, but their frequency and intensity have been increasing partly due to climate change (Surenkhuu & Boldbaatar, 2022, UNDP 2023). Climate change is exacerbating the situation, with Mongolia experiencing rapid warming and increased aridity (Sharma & Dalaibuyan, 2021). The impact of Dzuds on livestock can be devastating, with some events causing mortality rates of up to 30% of the national herd (Surenkhuu & Boldbaatar, 2022). From 2000 to 2014, Dzuds resulted in the death of approximately 30 million livestock, severely impacting Mongolia's socio-economy (Nandintsetseg et al., 2018). Recent data shows that the 2023-2024 Dzud affected 90% of Mongolia's territory, resulting in the loss of over 5.2 million livestock, or about 8% of the total livestock population (UNICEF, 2024).

The increasing frequency of Dzuds is attributed to a combination of climate-driven multi-hazards (47.3%) and socioeconomic vulnerability (46.2%) (Nandintsetseg et al., 2018). Climate factors include growing-season droughts followed by extreme cold and heavy snowfall, while vulnerability stems from livestock overpopulation and inadequate preparedness (Nandintsetseg et al., 2018; Chadraabal et al., 2022). Also, Sharma and Dalaibuyan (2021) highlight the complex interactions between Dzuds, traditional livestock herding and the growing mining sector in the country. Additionally, to climate change, environmental degradation from mining puts pressure on water resources and livelihoods (Sharma & Dalaibuyan, 2021).

The weakening of the polar jet stream, caused by rapid Arctic warming, may be allowing frigid polar air to reach Mongolia more easily (Sternberg, 2018). Additionally, Mongolia has experienced a 40% increase in average winter snowfall since 1961, which has a cooling effect and makes extreme cold more likely (Sternberg, 2018). These climate-driven disasters not only threaten herders' livelihoods but also impact the national economy, with GDP growth rates declining in response to severe Dzuds (Chadraabal et al., 2022).

The research by Roeckert & Kraehnert (2022) provides significant insights into the relationship between Dzuds and internal migration patterns in Mongolia. The study found that Dzuds cause substantial and statistically significant increases in both temporary and permanent migration from rural to urban areas. This effect is most pronounced in the year immediately following a Dzud event but can persist for up to three years after the disaster (Roeckert & Kraehnert, 2022). Interestingly, the research identified a threshold effect, with migration increasing only when livestock mortality rates exceed 10%. The study also revealed demographic patterns in migration responses, with young adults (aged 20-39) being more likely to migrate compared to other age groups. While both men and women migrate in response to Dzuds, the effect is slightly stronger for men. These findings highlight the significant impact of Dzuds on population dynamics and rural-urban migration in Mongolia, underscoring the need for climate change adaptation strategies that consider potential increases in internal migration due to extreme weather events.

4.5. Desertification

Desertification poses a significant threat to Mongolia's water resources and ecosystems, exacerbated by climate change and human activities. Approximately 77% of Mongolia's total territory has been affected by desertification and land degradation (Xinhua, 2023). This process is driven by a combination of factors, including rising temperatures, decreased precipitation, and overgrazing. Between 1940 and 2015, Mongolia's annual mean air temperature increased by over 2°C (Sharma & Dalaibuyan, 2021), while annual precipitation decreased by 7%, resulting in higher aridity across the country (Zhang et al., 2021). These climatic changes have led to a positive feedback loop between soil moisture deficits and surface warming, creating a hotter and drier climate (Zhang et al., 2021). Human activities, particularly overgrazing and irresponsible mining, have further accelerated desertification (Xinhua, 2023). The expansion of unpaved rural roads has also contributed to soil degradation, as drivers create new paths across the landscape (Xinhua, 2023). As a result of these combined pressures, more than three-quarters of Mongolia's land is now affected by drought and desertification, threatening water availability and the sustainability of traditional livelihoods (Zhang et al., 2021).

5. DATA ANALYSIS • Findings

5.1. Heatwaves

The threshold heatwave temperature for Mongolia was defined individually for each grid point. The historical baseline showed a mean probability of occurrence of 6% for heatwaves above this threshold lasting longer than five days (low hazard), and less than 1% for heatwaves for longer than 7 days and 10 days respectively (medium and high hazard).

Under the SSP scenario 1-2.6 the probability of occurrence for low hazard events starts at 25% (3 % and 1% for the medium- and high-hazard events respectively) and increases to around 60% (16% and 7% respectively) by mid-century but starts decreasing dramatically after that. At the end of the century the low-hazard probability is at around 20%, 4% and 1% and therefore lower than in 2024, implying that climate policies could start working.

Under the SSP scenario, 2-4.5, heatwaves are projected to become much more common (around 70% probability) by 2045, with corresponding probabilities for medium-hazard heatwaves and high-hazard heatwaves (20% and 3% respectively by mid-century). At the end of the projection period, all three hazard classifications have a significantly higher likelihood than in the status quo, with low-hazard at approximately 70%, medium hazard at just below 30% and high-hazard at 6%.

Under the SSP scenario, 5-8.5, heatwaves are projected to both get more frequent and more intense steadily until the low-hazard heatwaves reach almost 100% probability of occurrence by the end of the century. In comparison to the other two scenarios, medium-hazard and high-hazard heatwaves will increase more dramatically. At the end of the century, medium-hazard heatwaves have a likelihood of occurrence of more than 80% and high-hazard heatwaves have a likelihood of occurrence of approximately 60%.

Figure 1: Probability of occurrence of heatwaves for low hazard events

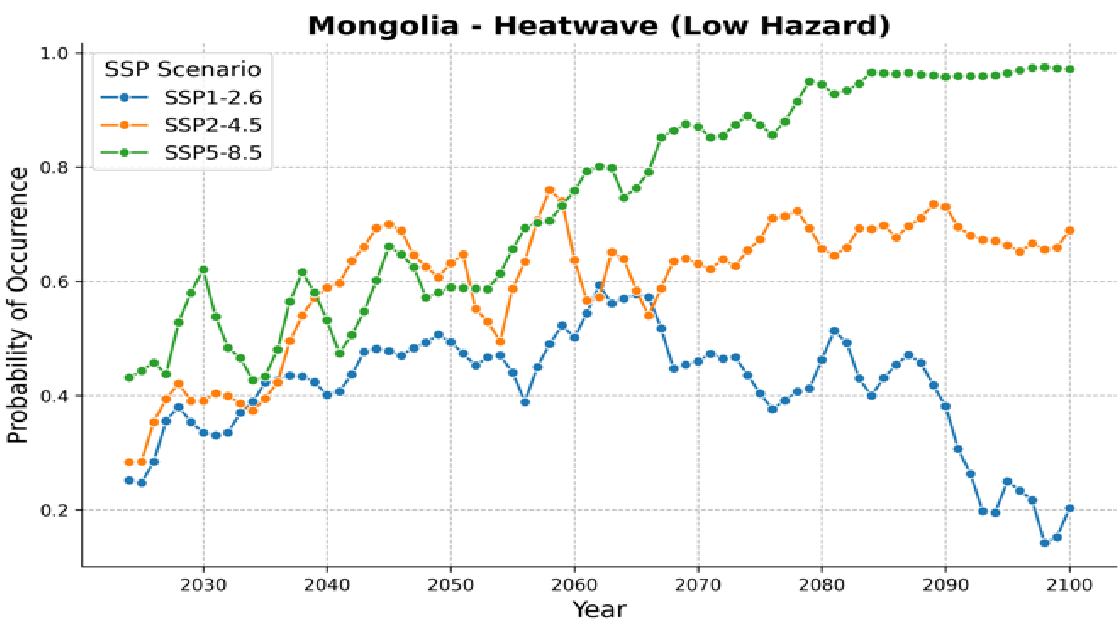


Figure 2: Probability of occurrence of heatwaves for medium hazard events

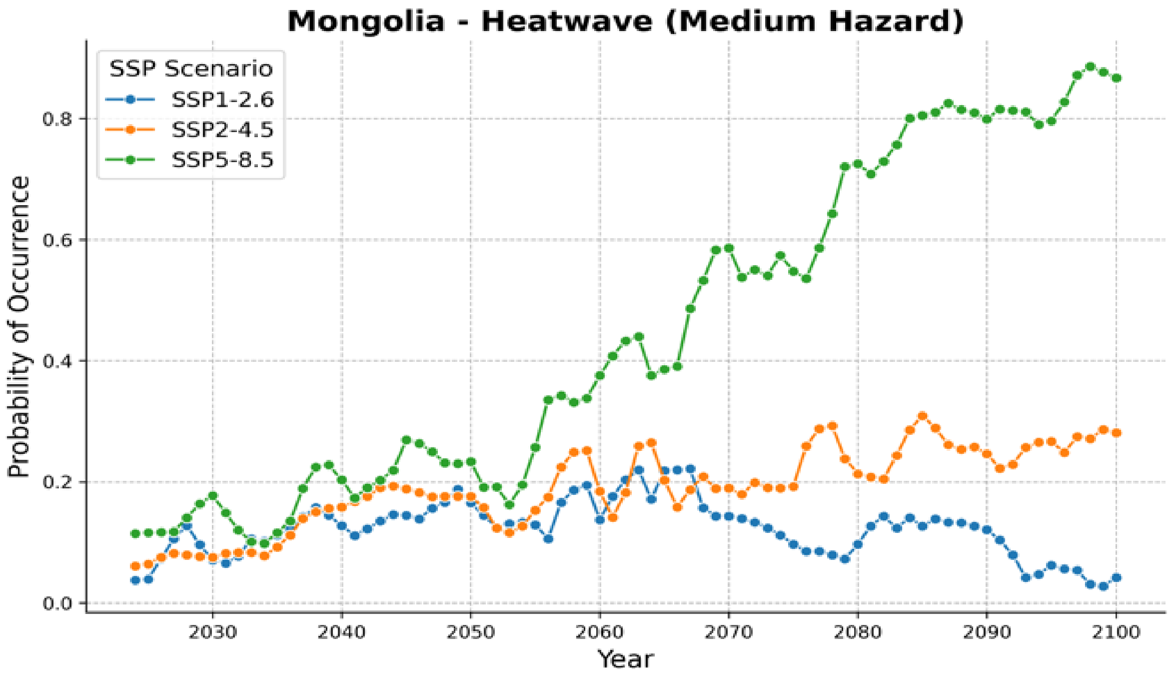
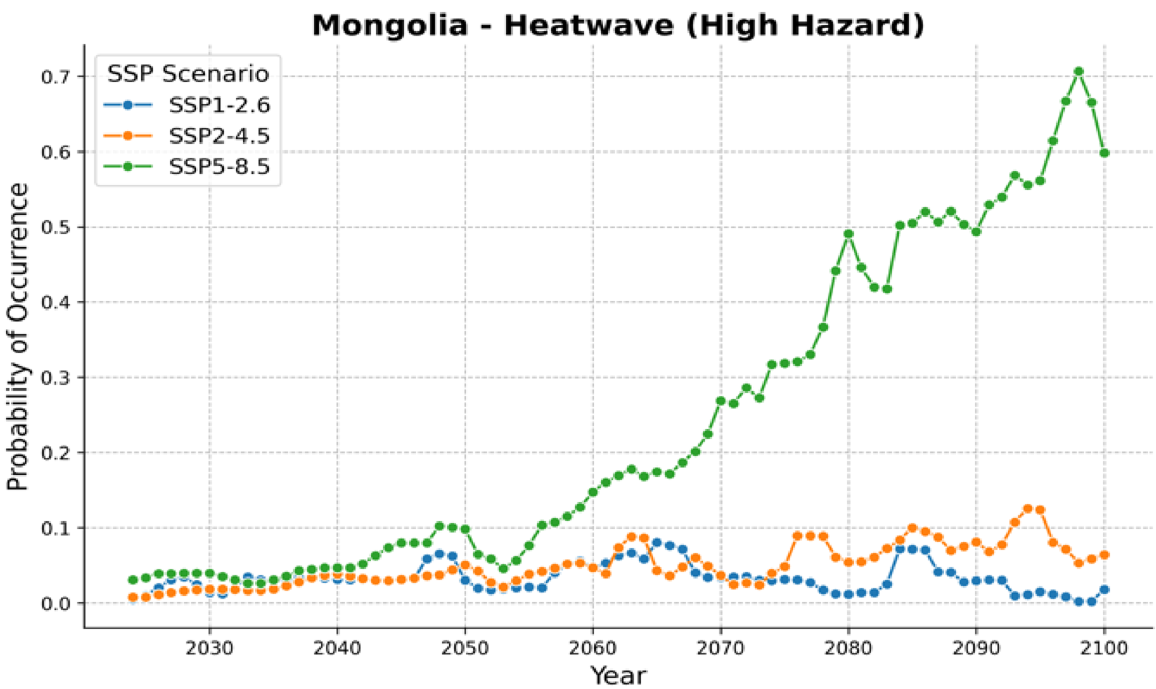


Figure 3: Probability of occurrence of heatwaves for high hazard events



5.2. Meteorological droughts

The mean probability for the historical baseline for the probability of occurrence of low-hazard drought events in Mongolia was 14% per annum and 3% and less than 1% for medium-hazard drought events and high-hazard drought events respectively. At the beginning of the projected period in 2024 the probability of occurrence was at approximately 20% for low hazard events (5% and <1%).

Please refer to the below figures for a visualization of the here described results. In the SSP 1-2.6 scenario, these probabilities remain comparably stable throughout the century and decrease to 16% (4% and <1%) at the end of the projected period. In the SSP 2-4.5 scenario the probabilities also remain relatively stable throughout the century for all three hazard classifications, but do not decrease at the end of the projected period but remain the same or increase instead. By 2100 the low hazard probability of occurrence is still approximately 20%, while the medium-hazard probability of occurrence is projected to be at 6% and the high-hazard probability of occurrence is at around 1%.

In the SSP 5-8.5 scenario, the likelihood of drought rises significantly for all three hazard classifications to around 30% in low-hazard, to 13% for medium-hazard and to around 3% for high-hazard.

Figure 4: Probability of occurrence of meteorological droughts for low hazard events

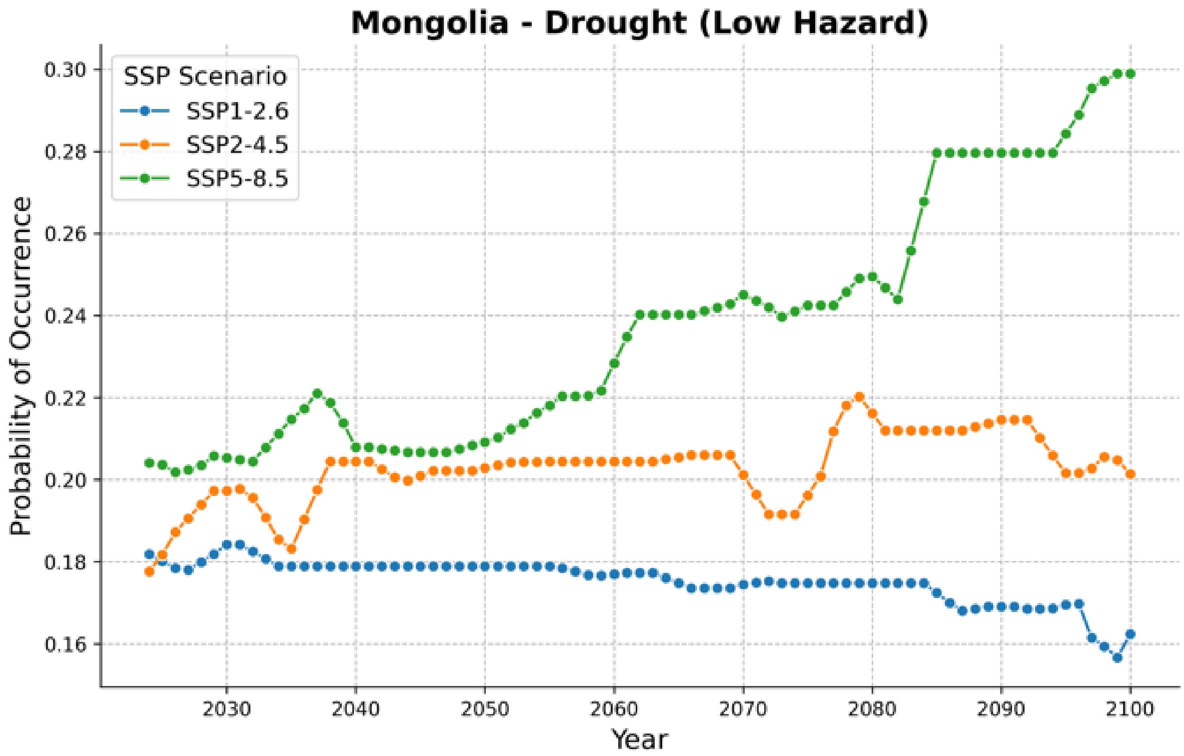


Figure 5: Probability of occurrence of meteorological droughts for medium hazard events

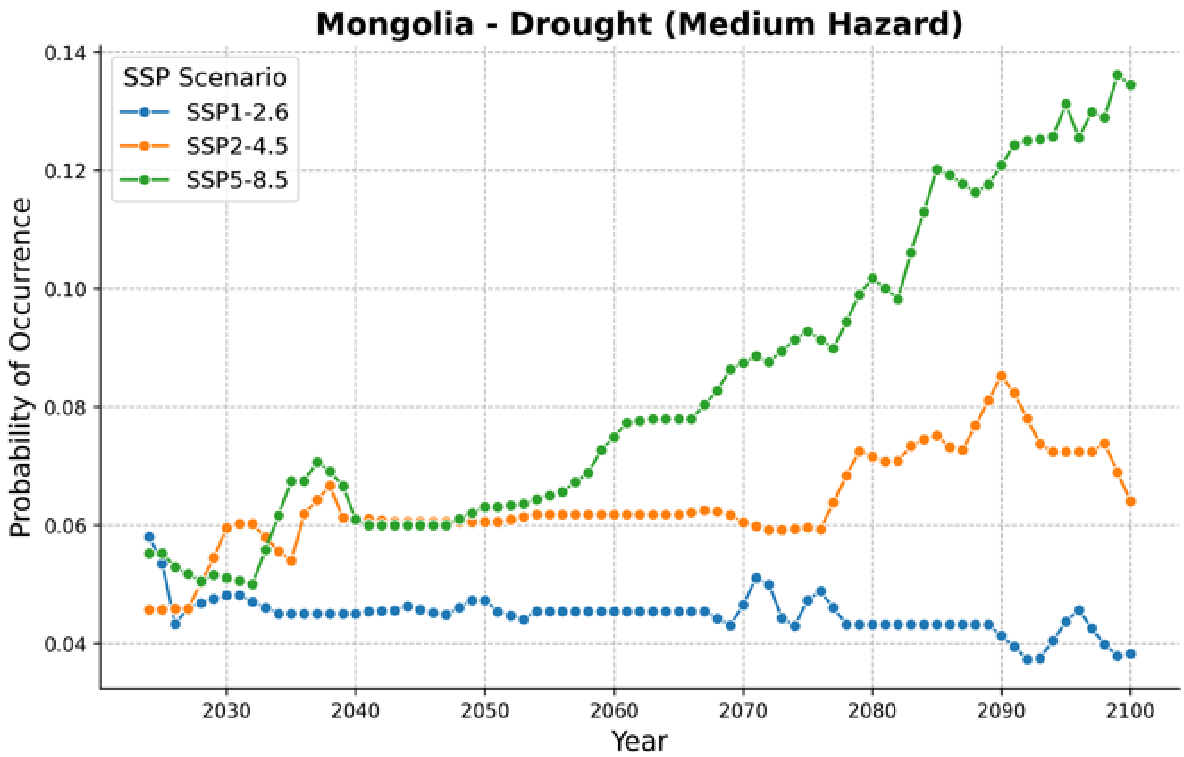
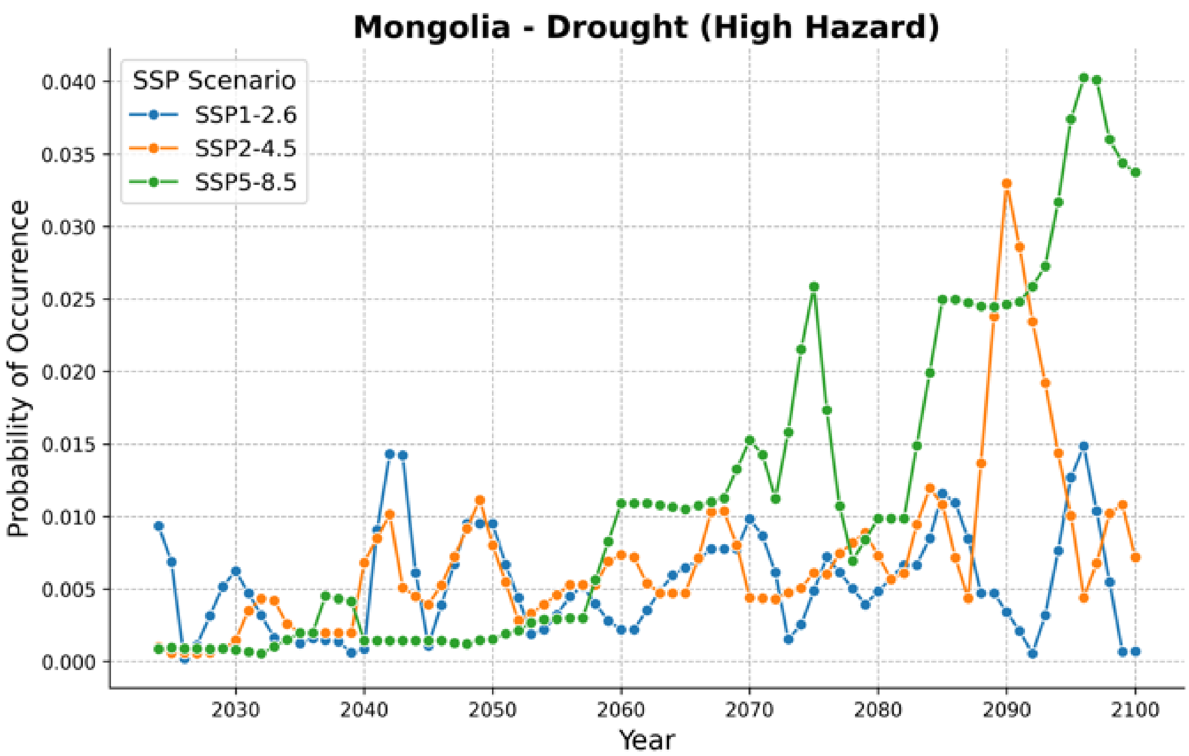


Figure 6: Probability of occurrence of meteorological droughts for high hazard events



5.3. Riverine floods

The mean probability of occurrence during the baseline period for low-hazard floods was 20% in Mongolia and 10% for medium-hazard floods and just above 2% for high-hazard floods, corresponding to 5-year flood risks, 10-year flood risks and 100-year flood risk in the baseline period These numbers change to around 45% by 2024 and to 26% and 5% by 2024, with moderate variations depending on the scenario. Please refer to the below figures for a visualization of the here described results In the SSP 1-2.6 scenario, the risk for floods rises initially in the first half of the century but stabilizes throughout and reaches similar levels again at 47% by 2100 for low-hazard events and 27% and 6% for medium- and high-hazard events respectively. In the SSP 2-4.5 scenario, the probability for all three hazard classifications rises steadily throughout the century but goes down again slightly towards the end of the century from the highest peak, ending the projection at 70% for low-hazard flood events and at 48% and 10% for the other classifications. This shows that this scenario will particularly increase low- and medium-hazard flood events, but not very severe flood-events. In the SSP 5-8.5 scenario, the probability for all three flood classifications rises dramatically, in particular the probabilities for low-hazard events and medium-hazard events, ending the projected period at approximately 93% and 80% respectively, which could have devastating effects. Correspondingly, the high-hazard events are also projected to rise to 25% per annum.

Figure 7: Probability of occurrence of riverine floods for low hazard events

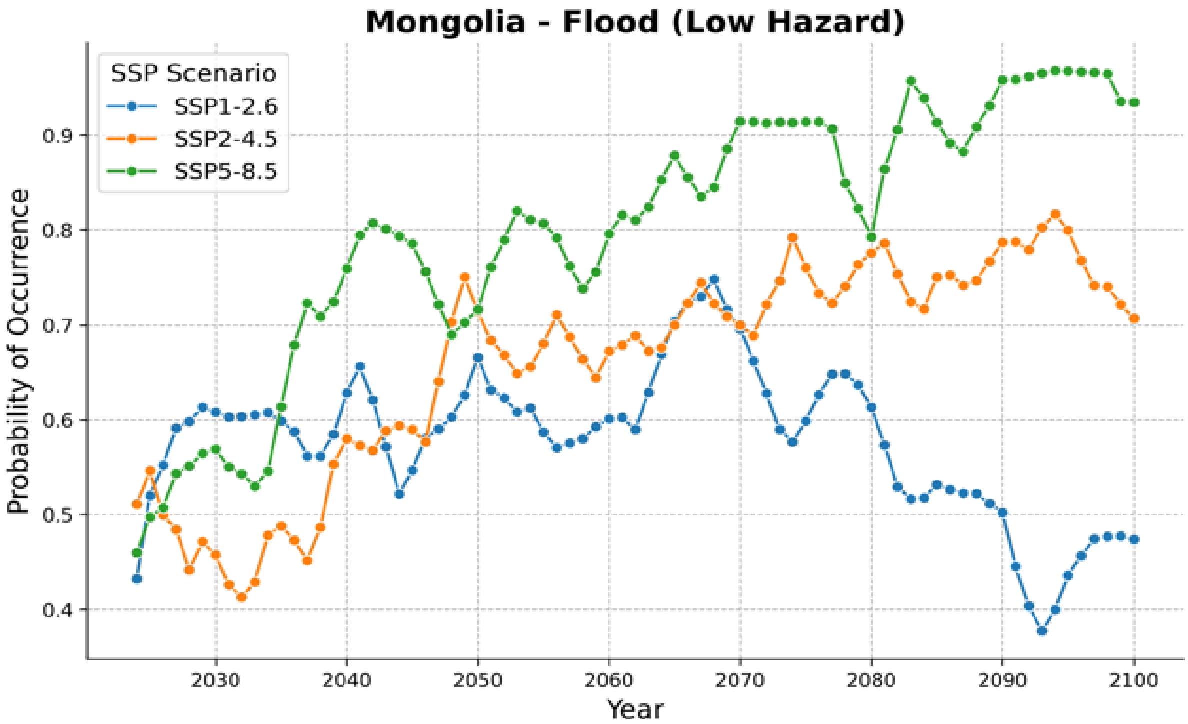


Figure 8: Probability of occurrence of riverine floods for medium hazard events

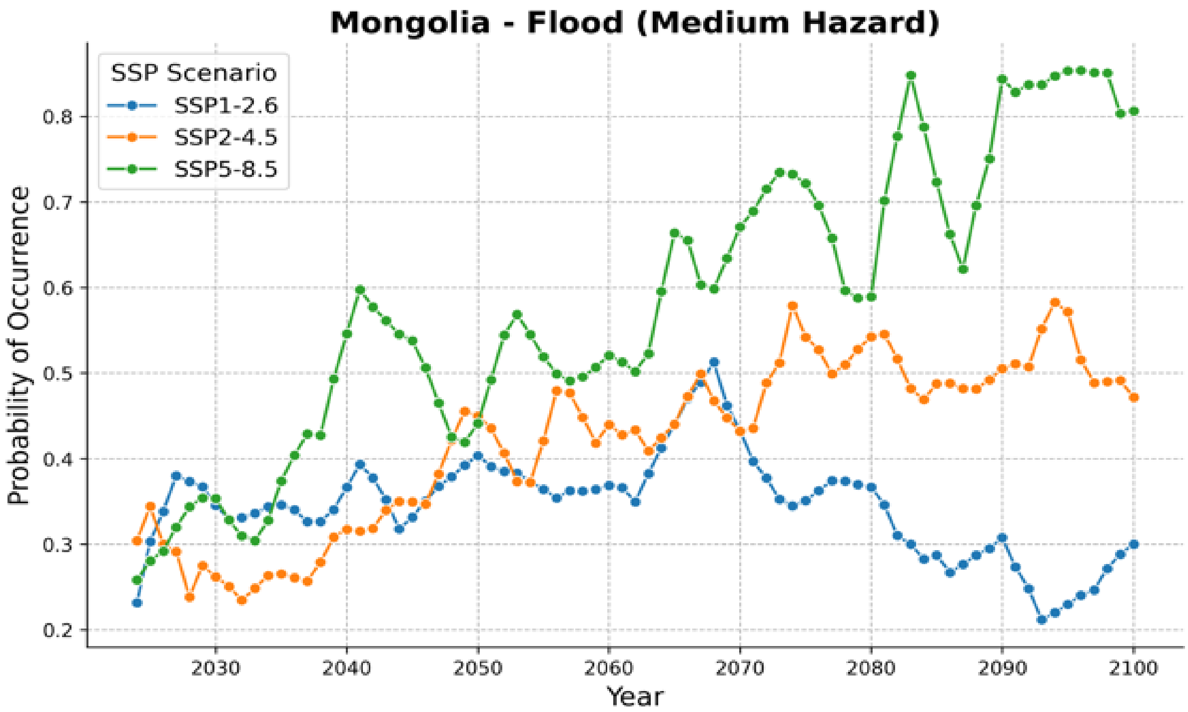
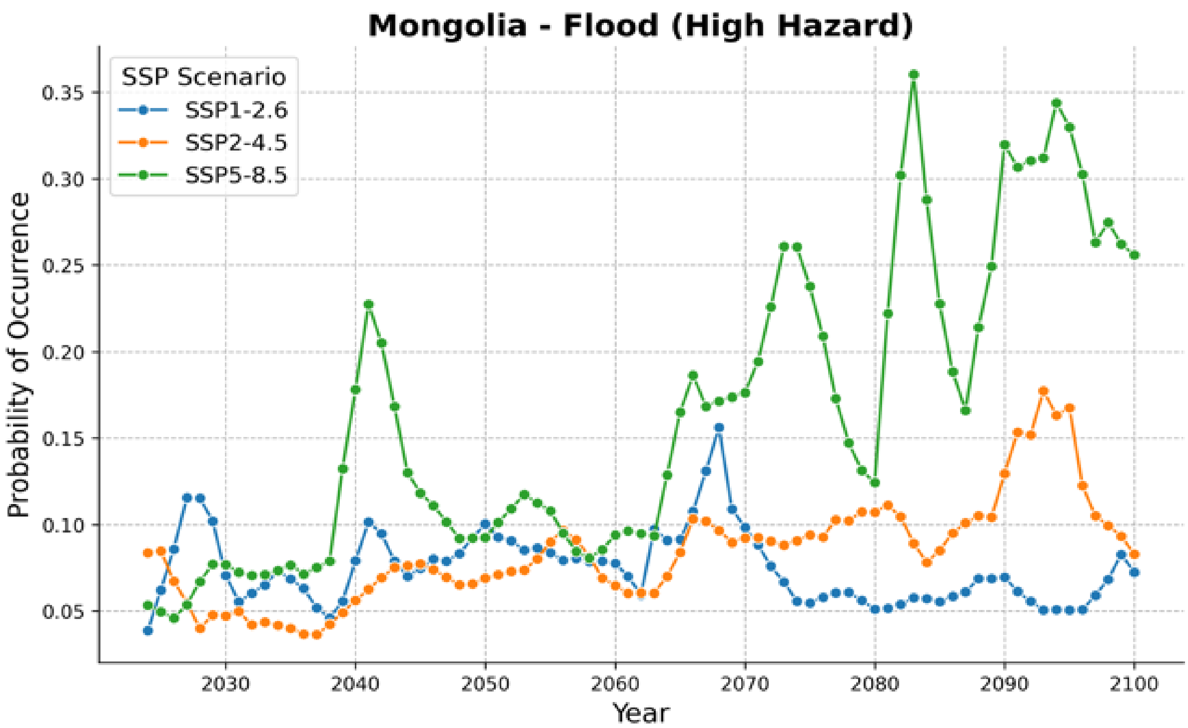


Figure 9: Probability of occurrence of riverine floods for high hazard events



5.4. Evaluation

The projected climate trajectories for Mongolia reveal escalating risks from heatwaves, droughts, and riverine floods under various SSP scenarios, with severe implications for ecosystems, water resources, and public health infrastructure, in particular under high-emission scenarios. This evaluation synthesizes these findings to discuss the potential long-term impacts and the critical need for both mitigation and adaptation strategies.

Heatwave projections indicate that Mongolia could experience a significant increase in both the frequency and intensity of heat events. By mid-century, the probability of occurrence for short-duration heatwaves is projected to be as high as 70% under SSP 2-4.5 and approaches near-certainty under SSP 5-8.5, where high-intensity heatwaves (lasting more than ten days) become probable. The consequences for Mongolia's climate-sensitive environments, notably its steppe and desert ecosystems, include potential loss of biodiversity, increased wildfire risks, and ecosystem shifts. Additionally, extended heatwaves will exacerbate health risks, increasing heat-related illnesses and mortality, particularly in vulnerable populations, and intensify strain on Mongolia's under-resourced health systems. Furthermore, the economic costs of prolonged ad frequent heatwaves could be devastating for the national budget and economy, leading to a permanent state of emergency to adapt to an ever-increasing likelihood of severe heatwaves.

Drought patterns remain relatively stable under SSP 1-2.6 and SSP 2-4.5, suggesting that moderate emissions reductions could maintain drought frequencies close to historical baselines. However, under SSP 5-8.5, the annual probability for low- and medium-intensity droughts reaches 30% and 13%, respectively, highlighting a greater risk of sustained dry periods. This outcome would lead to significant hydrological stress, particularly in rural areas reliant on surface and groundwater sources for agriculture and livestock. Extended droughts could exacerbate desertification, reducing arable land, threatening Mongolia's livestock-based economy, and prompting migration from rural areas, which could intensify socio-economic pressures on urban centres. In this worst-case scenario, whole sectors of the economy and an already vulnerable sub-group of the population could be negatively affected and slip into poverty.

Flooding risks under SSP 5-8.5 exhibit dramatic increases in frequency, with low-hazard events projected to reach an 93% annual probability and medium-hazard events nearing 80% by century's end. Even SSP 2-4.5 sees a steady rise in flood probabilities throughout the century. The implications of this trend are far-reaching, with potential consequences for infrastructure resilience, water quality, and public health. Repeated flooding could erode soil, disrupt agricultural productivity, and damage critical infrastructure, including roads, bridges, and energy facilities. Additionally, increased flood frequency elevates risks of waterborne diseases, especially in communities lacking robust sanitation systems. The combined effect of high flood frequency with heat-induced strain could further destabilize Mongolia's agriculture sector and its economy, creating feedback loops that exacerbate resource scarcity.

The climate projections indicate that without substantial global mitigation efforts, Mongolia's water-related hazards will intensify, with potentially severe socio-economic and environmental impacts. The SSP 1-2.6 scenario suggests that emission reduction policies could not only stabilize but reduce the probability of some hazards by the century's end. However, high-emission pathways imply a near-certain increase in extreme heatwaves, droughts, and floods, which would require substantial adaptation measures to protect human and ecological systems.

For Mongolia, this means prioritizing adaptation strategies such as enhanced water management policies, early warning systems, and infrastructure reinforcement to mitigate flood impacts. Building climate-resilient infrastructure and expanding public health capacity to handle extreme heat and flood events are also critical. Moreover, land and agricultural management practices that increase soil resilience to drought and reduce desertification will be essential in sustaining rural livelihoods. While adaptation can mitigate immediate impacts, the effectiveness of these strategies remains contingent on the broader commitment to global emission reductions to avoid the most severe outcomes projected under high-emission scenarios.

In conclusion, Mongolia's projected climate hazards underscore the urgent need for a dual approach: aggressive global mitigation efforts to limit hazard escalation and robust national adaptation to enhance resilience against unavoidable climate impacts.

6. ECONOMIC DAMAGES

In light of recent and upcoming climatic changes, it's also necessary to look closely at economic damages that are caused by the aforementioned events. Heatwaves, droughts and floods can have dramatic effects on individual economic sectors, particularly on agriculture, human health and the energy market. Generally speaking, global annual damages from climate change are estimated to be 38 trillion US-American dollars by 2050, with developing nations such as Mongolia being particularly vulnerable and affected (PIK 2024).

Mongolia has faced increasingly severe heatwaves over the past 30 years and is projected to continue doing so. This development has caused immense costs to the Mongolian economy. Extreme heat events in the summers at the beginning of the millenium led to widespread drought, which, coupled with winter Dzuds, killed millions of animals. Between 1999 and 2002, over 8.6 million livestock perished, causing direct economic losses estimated at around $130 million annually during that period (Ravsal 2003).

Correspondingly, droughts have caused significant crop production declines in Mongolia with severe impacts on the agricultural sector. During the 2004 drought, 30-50% reductions in Net Primary Productivity (NPP) were detected in severely affected areas, with some regions experiencing 50-75% decreases (Nanzad et al. 2021). Similarly, the 2015 drought, which experts consider to have been one of the worst in years, severely affected cropped areas and caused deterioration of pastures and rangeland conditions and, as a consequence, led to a significant increase in wheat imports in 2017, reaching 13.6 thousand tons, which was 10 times more than in 2016 (Battsetseg, 2024).

Lastly, floods have also caused immense damages to the Mongolian economy, which is a trend that is mirrored globally. The last IPCC report suggested an 1.2 to 1.8-fold increase in average GDP losses due to flooding between 1.5°C and 2°C warming (Caretta et al., 2022). Flooding in Mongolia, though less frequent than droughts, has become more common due to changing precipitation patterns and more intense rainfall events. The economic impact has been substantial, particularly in urban areas. For instance, In recent years, Ulaanbaatar, the capital city of Mongolia, has experienced significant flooding events that have caused substantial damage to urban infrastructure and transportation networks. In 2018, a series of in Ulaanbaatar caused damage worth approximately $12 million, affecting transportation networks and urban infrastructure. Cumulatively, infrastructure repair and replacement costs due to floods over the past two decades are estimated at over $150 million (Give2Asia, 2019). It's important to note that the cumulative impact over the last two to three decades of the water-related climate hazards drought, floods and heatwaves are likely to be significantly higher, but reliable data remains difficult to obtain. Total damages to agriculture, livestock losses and infrastructure are difficult to estimate but are likely to go far beyond the aforementioned numbers.

7. ADAPTATION MEASURES

The following chapter will provide two in-depth suggestions for adaptation measures based on the findings of the data of this report. These suggestions should be regarded as additional findings to existing or planned adaptation measures and do not represent a full analysis of the status quo. Both measures are preliminary approaches and should be further investigated with the help of economic modelling and cost-benefit analyses.

The measures identified were chosen based on a number of reasons:

- Relevance to identified hazards: The measures directly address the primary climate hazards identified in the data analysis. They therefore respond to ongoing challenges, helping to mitigate the immediate impacts on the agriculture and hydropower sectors.
- Alignment with sectoral and regional needs: The measures kept small-scale and medium-scale farmers in mind as well as regional acuteness for the identified hazards.
- Feasibility: Measures were selected based on their feasibility of implementation and on success in similar sectors.
- Co-benefits: Suggestions aim to provide multiple benefits beyond addressing the primary climate hazard.
- Integration with existing efforts: Measures were chosen for their complementarity with ongoing projects and efforts.

Following that, this chapter provides a list of additional adaptation suggestions that could be explored in the future.

7.1. Mobile greenhouse systems

Sector: Agriculture

Hazard: Drought, Heatwaves

Region: Khangai Mountains, Altai Mountains

Background: Both arable farming and cattle farming are under increasing climatic pressure from droughts and heatwaves. This development will in all likelihood deteriorate in the next 80 years when faced with climate predictions. The structure of pastoralist and herding communities in Mongolia is particularly vulnerable to changing climatic conditions such as drought, heatwaves and worsening Dzud due to reduced forage, water resources, decreasing snow levels, and lack the resilience of those who live in more permanent settlements (Chuluun 2014). This challenge is intensified in the north and south of Mongolia where herders move less and are not as flexible in their choice of destination (Kakinuma 2024). As a consequence, food security issues will also increase. Mobile greenhouses are portable structures designed to provide a controlled environment for growing plants, particularly in areas with challenging climates or limited resources. These innovative solutions offer several benefits for agriculture in developing countries and regions facing environmental challenges. They offer applications such as year-round use, water efficiency and a local production of a variety of crops (RESET 2020). The relatively new development is already in place with GRO in Sierra Leone and Mozambique (World Hope 2024).

Current efforts: Spirit of America, in collaboration with the US Embassy and local partners, supported the construction of a solar-paneled well and greenhouse for herders in the

Gobi Desert to address issues such as water scarcity and food security concerns. The project has successfully cultivated 15 types of vegetables and combated overgrazing in the Gobi desert (Spirit of America 2024). Another project is the "Greenhouse Development Project" by Sain Tus Centre NGO. The Associated Country Women of the World (ACWW) funded a project to develop two greenhouses in the Khovd Aimag region of Mongolia, which has shown promising results in the fields of unemployment, expanded crop variety and expected harvests. These initiatives demonstrate Mongolia's growing interest in innovative greenhouse solutions to address challenges in agriculture, food security, and economic development in harsh climatic conditions.

Suggestion: The introduction of portable, climate-controlled greenhouses that can be moved to different locations depending on weather conditions or seasonal needs. These greenhouses are designed to extend the growing season by protecting crops from harsh weather like frost, heat, and wind. They offer flexibility, allowing farmers or herders to grow vegetables, fodder, or even medicinal plants in regions where traditional agriculture is difficult due to extreme temperatures and limited water.

Suggested measures:

- Funding of initial investment costs through grants or loans for herders/farmers in vulnerable positions by state or international partners.
- Construction of solar-powered greenhouses where possible to increase efficiency and cost effectiveness.
- Modular design: The greenhouses should be modular and lightweight to allow for ease of transportation. Modular sections can be constructed out of metal or reinforced plastic frames with a covering made from UV-resistant polyethylene.
- Integration of drip irrigation systems to ensure efficient water use. For added resilience, consider using captured rainwater or graywater recycling for irrigation, which would further reduce water demand

Expected benefits:

- Improved climate resilience through year-round protection.
- More efficient use of water resources.
- Poverty alleviation by allowing farmers to become more self-sufficient, avoid costly imports and to sell excess produce.
- Protection from both heat and frost conditions.

7.2. Climate-resilient fodder protection

Sector: Agriculture

Hazard: Dzuds

Region: Eastern Steppe, Khangai, Altai regions

Background: Climate change is leading to more severe Dzuds and extreme conditions for herders and their respective cattle with an increasing number of animal losses. Fodder and feed protection is an important part of the strategy to combat these effects. Through access to adequate feed in winter and a focus on healthy body conditions for the rest of year, the animal losses can be significantly reduced (Rasmussen et al. 2011). Climate-resilient fodder protection is an important adaptation strategy for livestock management in regions facing climate change impacts, particularly in Mongolia where herders are vulnerable to extreme weather events. It involves various practices to ensure a stable supply of animal feed, even in the face of adverse weather conditions. Since the update of its nationally determined contributions (NDC), Mongolia has focused its adaptation efforts on animal husbandry, pastureland management and arable farming. This includes disaster management for harsh conditions (FAO 2024).

Current efforts: As part of the national adaptation efforts Mongolia has been implementing practices to protect animal husbandry, herding and fodder supply such as community-based resource management where Herders coordinate on rotational pastures and sustainable use of water resources and haymaking storage to establish pastures reserves (UNDP 2024).

Suggestion: A national or regional development of strategies to ensure the availability of fodder during extreme climate events.

Suggested measures:

- Establishment of regional, centralized fodder banks where fodder is stored during surplus periods (such as summer) for use during winter or during Dzud events. The fodder can be distributed to herders during emergencies to prevent mass livestock die-offs. Fodder banks can be regulated through communal governments.
- Introduction of more climate-resilient fodder crops such as lucerne.
- Fencing and planting strips: Establishing Forest, fodder plant, and technical plant strips around arable croplands to protect soil moisture and reduce wind erosion.

Expected benefits:

- Improved livestock survival during Dzud periods through the emergency fodder bank system.
- Reduction of overgrazing.
- An increase in economic security for herders and farmers.

7.3. Additional suggested adaptation measures

► The improvement of water quality should be of upmost importance in order to avoid further water contamination in a country that is already under pressure regarding water resources. Contaminated water is not only problematic for human health reasons but can threaten Mongolian herders' livelihoods as livestock is the only source of income for many families. If cattle dies or falls ill due to contaminated water, the repercussions are manifold including a lack of financial safety options and lack of ensuing economic opportunities (Boehm et al, 2017).

► The facilitation of cross-sectoral partnerships. Research has shown that partnerships between mining companies, herders, and local governments could help address sustainability challenges and support climate change adaptation efforts. Furthermore, this should be taken to the policy-level in order to promote sustainable development in Mongolia (Sharma & Dalaibuyan, 2021).

► Monitoring and prediction of Dzuds (Surenkhuu & Boldbaatar, 2022): emphasizing the need for improved monitoring and prediction systems to mitigate their impacts on Mongolia's livestock sector, economy and migration. Nevertheless it is challenging to accurately predict Dzuds due to their complex nature and the interplay of multiple environmental factors (Surenkhuu & Boldbaatar, 2022).

► Water Harvesting: Although Mongolia has made some efforts in water saving in regions that are particularly prone to drought and desertification, more modern approaches could be adopted. This could include the construction of small-scale water retention structures, such as check dams and contour trenches, to capture and store rainwater during wet periods (Wignaraja/Dimovska, 2024).

8. CONCLUSION

Mongolia faces intensifying water-related challenges as climate change amplifies the frequency and severity of hazards like droughts, floods, and extreme heat. The rising temperature and shifting precipitation patterns over the past decades have placed Mongolia's ecosystems, water resources, and economy under increasing strain. The GIZ project aims to address these critical issues by identifying cost-effective, tailored adaptation measures to support Mongolia's resilience. The comprehensive analysis of historical and projected climate data has led to crucial findings on hazard patterns and probabilities of occurrence, underscoring the urgency of adaptation strategies to mitigate these escalating risks effectively.

Mongolia has already experienced pronounced warming, with the average temperature rising by 2°C over the past 70 years, driving significant ecological and socio-economic impacts. Rainfall patterns have shifted, moving from light, consistent showers to erratic heavy rains. This change has contributed to a sharp increase in flooding events, posing threats to urban infrastructure, particularly in Ulaanbaatar's densely populated areas and informal settlements. Additionally, the combination of droughts and a uniquely Mongolian hazard known as *Dzuds* presents significant risks to the pastoral economy. Dzuds lead to high livestock mortality rates, impacting rural livelihoods and increasing the pressure on urban centers as displaced herders seek new means of survival.

Drought remains one of the most pervasive and destructive hazards for Mongolia, affecting water availability, agriculture, and pastoral systems. Mongolia's arid and semi-arid landscapes make it particularly vulnerable to prolonged dry periods, which diminish pasture quality, reduce crop yields, and accelerate desertification. Severe droughts in past decades have caused economic hardship and widespread livestock losses, underscoring the need for sustained drought management strategies. While low-emission scenarios suggest a relatively stable drought frequency, high-emission scenarios, such as SSP 5-8.5, project a significant increase in drought probability by 2100, leading to severe hydrological stress. This, in turn, could impact water supplies and agricultural productivity, prompting rural-to-urban migration and heightening socio-economic pressures.

Heatwaves are also expected to intensify, with significant increases in both frequency and duration, particularly under high-emission pathways. Projected probabilities indicate that short-duration heatwaves could become nearly certain under SSP 5-8.5, with high-intensity events lasting more than ten days likely to occur. These extreme heat conditions will pose major public health challenges, especially for vulnerable populations. Moreover, prolonged heatwaves increase the risk of wildfires, threaten Mongolia's grasslands and desert ecosystems, and heighten strain on water resources and agriculture. The economic costs associated with managing frequent and intense heat events could be substantial, further burdening Mongolia's budget and resources.

Flooding is another rising concern, exacerbated by erratic rainfall and the shifting climate. Although less frequent than drought, floods have increasingly impacted Mongolia, particularly in the past two decades, with events like those of 2016 and 2018 causing significant infrastructure damage. High-emission scenarios project a dramatic increase in flood probability, with low-hazard events potentially reaching an 80% annual likelihood by the century's end. This trend poses serious threats to infrastructure, public health, and water quality, with consequences extending to agricultural productivity and rural livelihoods. The intersection of frequent flooding and drought risks could create feedback loops, further destabilizing resources and increasing competition for scarce water.

The analysis reveals that if global emission trajectories remain high, Mongolia's water-related hazards will worsen substantially, with cascading impacts on human health, ecosystems, and the economy. Adaptation measures are essential to address these risks, but the success of these strategies also depends on broader global mitigation efforts to reduce greenhouse gas emissions. Under a lower-emission scenario like SSP 1-2.6, the likelihood of extreme events could decrease by the century's end, providing a window for stabilization. However, without mitigation, high-emission pathways suggest that Mongolia will face an almost certain increase in extreme heatwaves, droughts, and floods.

To address these impending challenges, Mongolia must prioritize robust adaptation strategies. Key measures include strengthening water management policies, establishing early warning systems, and reinforcing infrastructure to withstand floods and heatwaves. Enhancing public health capacity, especially to cope with extreme heat and waterborne diseases following floods, is critical for protecting vulnerable populations. Agricultural management practices that support soil resilience to drought and combat desertification will also play a crucial role in sustaining rural economies. Suggested adaptation measures, such as climate-resistant fodder and mobile greenhouses, could further protect Mongolia's livestock and agricultural systems, allowing communities to maintain livelihoods despite increasing climate pressures.

Ultimately, Mongolia's projected climate hazards point to a pressing need for a dual strategy: aggressive global mitigation to reduce the extent of climate impacts and comprehensive national adaptation to build resilience against the unavoidable challenges ahead. Through a combination of emission reductions and adaptive responses, Mongolia can better prepare for a future in which water-related hazards will increasingly shape its socio-economic and environmental landscape.

9. LITERATURE

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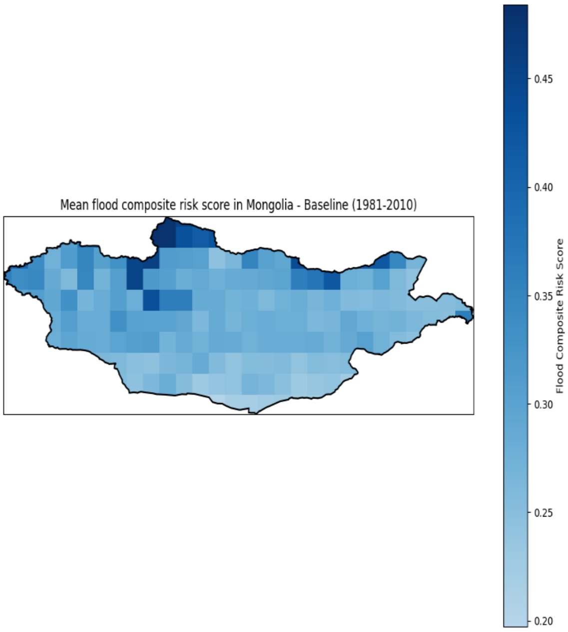
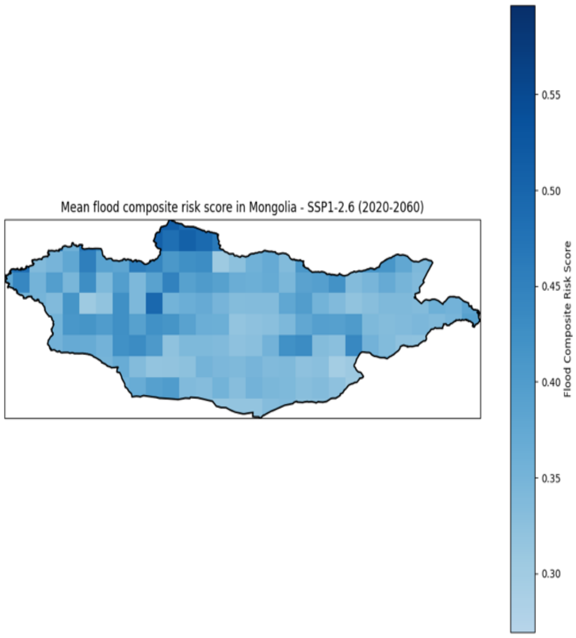
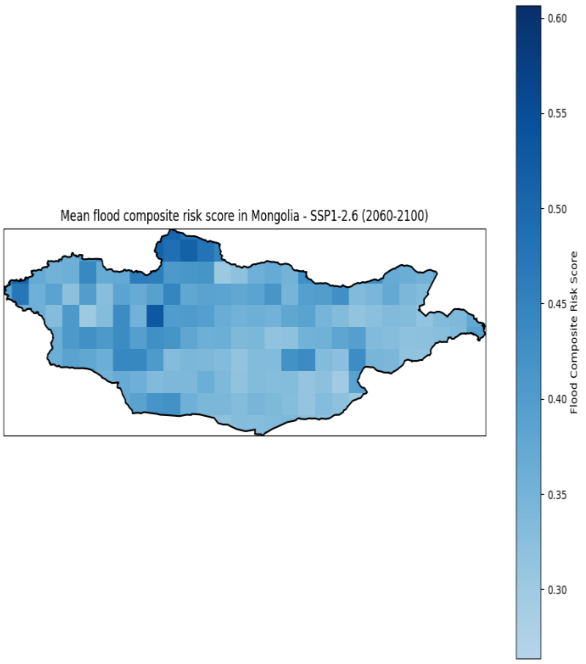
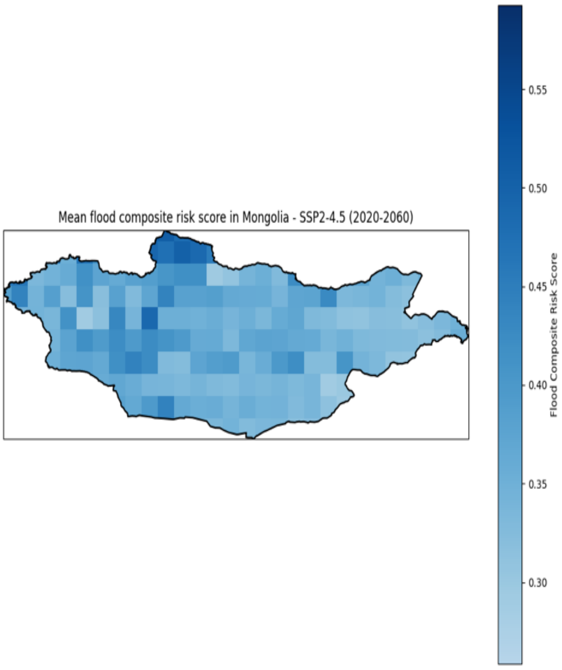
10. ANNEX • Figures for selected water-related hazards

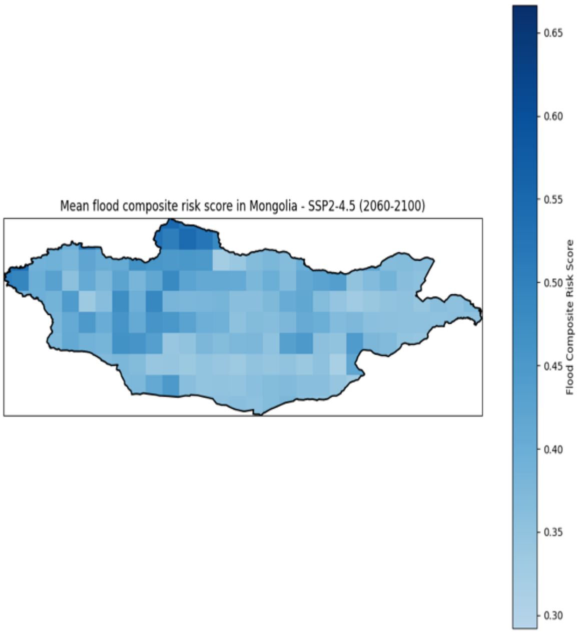
10.1. Mean flood composite risk score

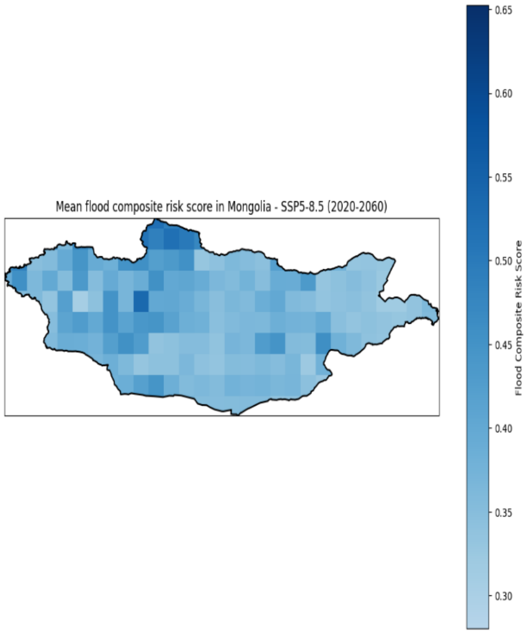


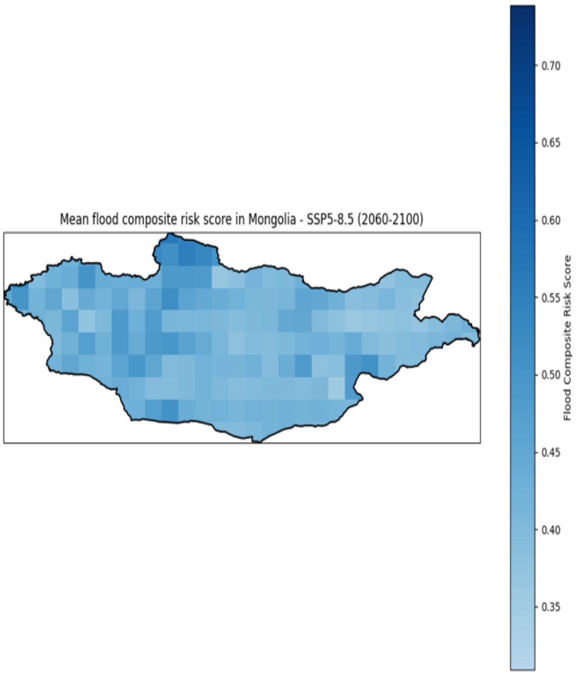




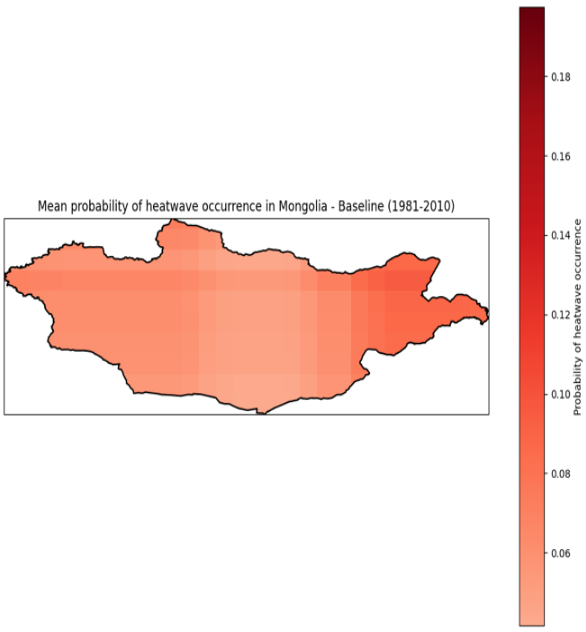


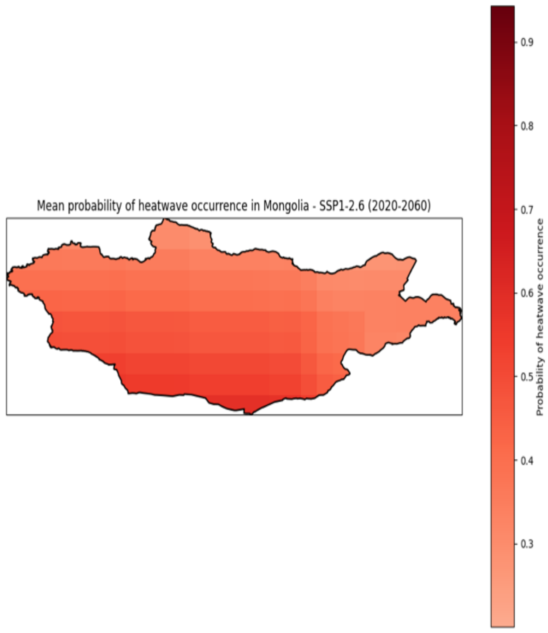

Mean flood composite risk score in Mongolia - SSP2-4.5 (2060-2100)
Flood Composite Risk Score
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30

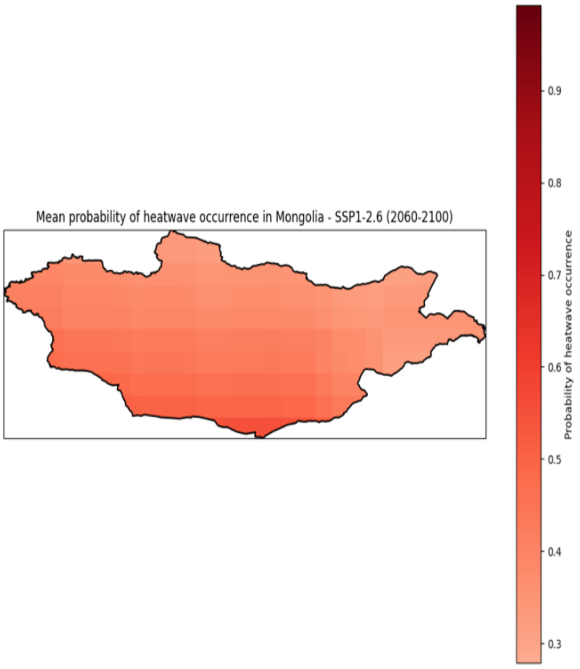

Mean flood composite risk score in Mongolia - SSP5-8.5 (2020-2060)
Flood Composite Risk Score
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30

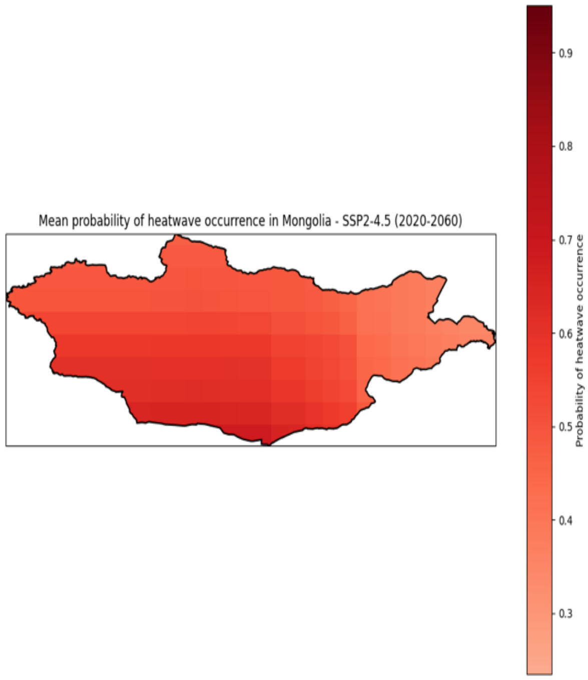

Mean flood composite risk score in Mongolia - SSP5-8.5 (2060-2100)
Flood Composite Risk Score
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35

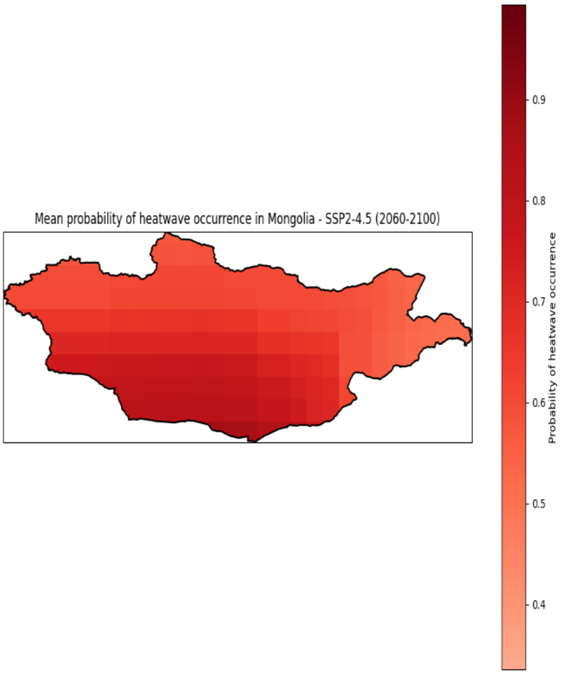
10.2. Heatwave probability

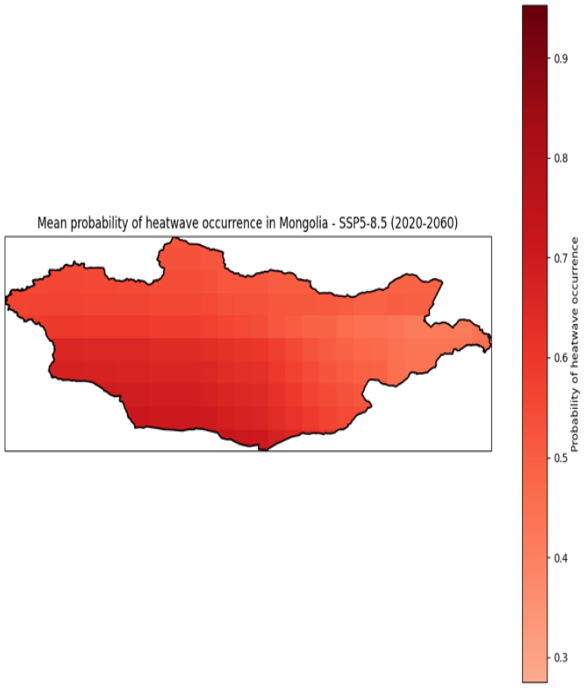


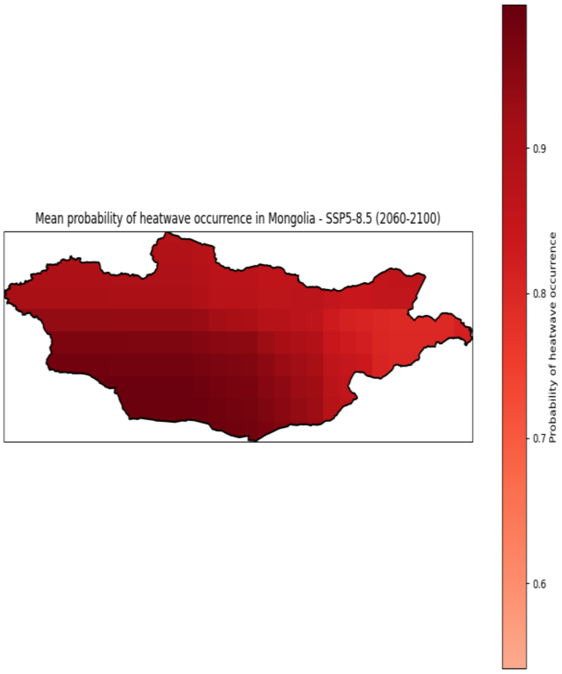




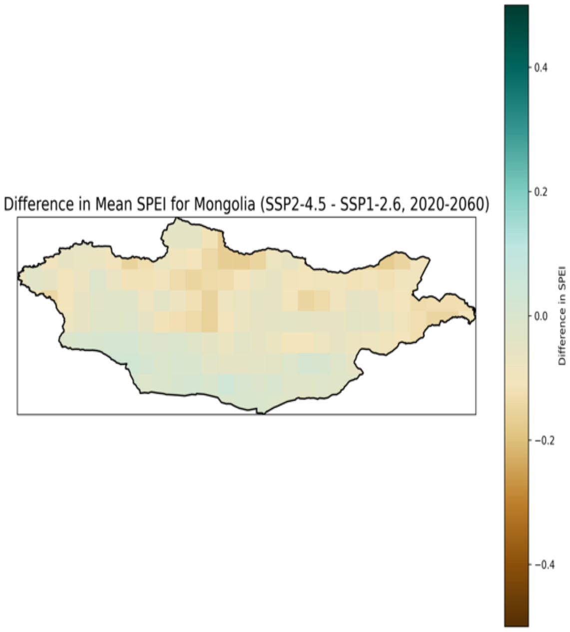


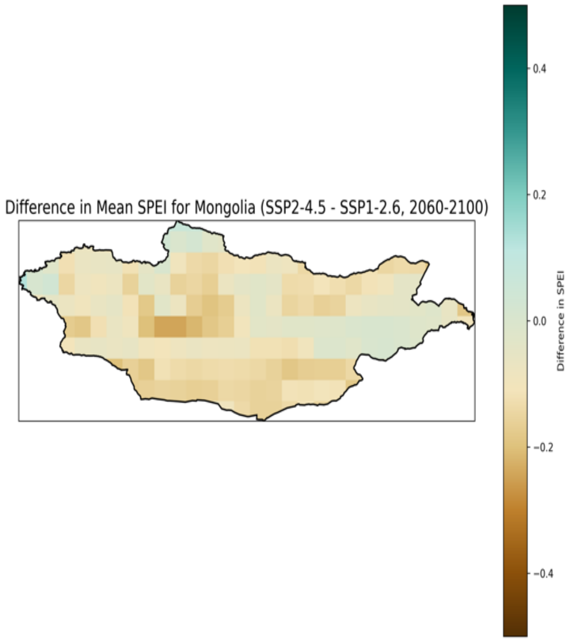

Mean probability of heatwave occurrence in Mongolia - SSP2-4.5 (2060-2100)
Probability of heatwave occurrence
0.9
0.8
0.7
0.6
0.5
0.4

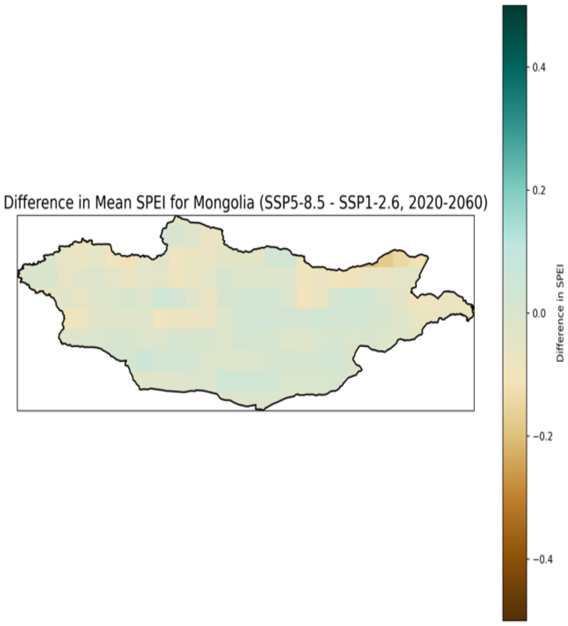

Mean probability of heatwave occurrence in Mongolia - SSP5-8.5 (2020-2060)
Probability of heatwave occurrence
0.9
0.8
0.7
0.6
0.5
0.4
0.3

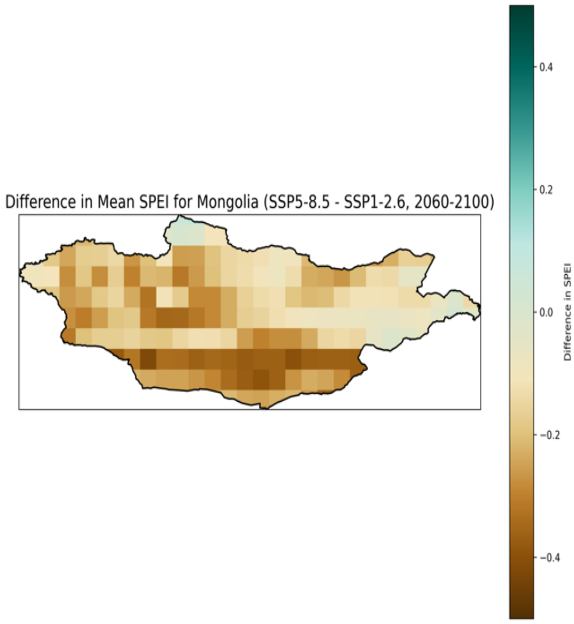

Mean probability of heatwave occurrence in Mongolia - SSP5-8.5 (2060-2100)
Probability of heatwave occurrence
0.9
0.8
0.7
0.6

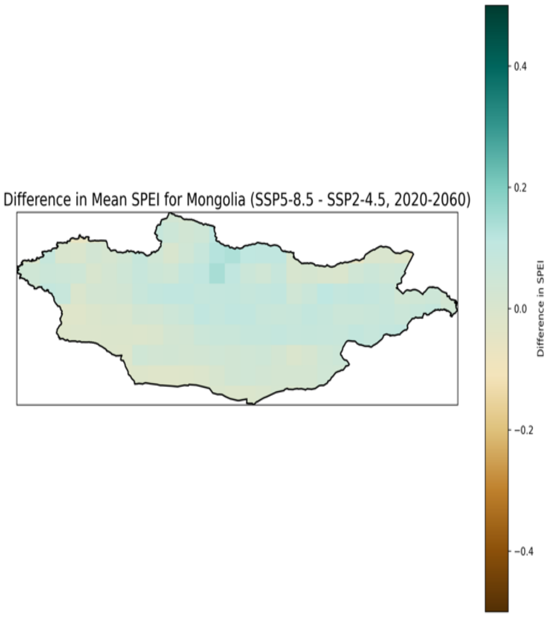
10.3. Differences in mean SPEI

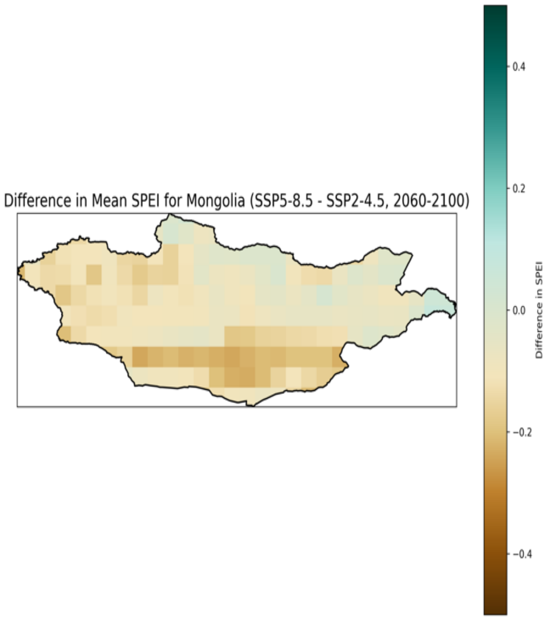









Difference in Mean SPEI for Mongolia (SSP5-8.5 - SSP2-4.5, 2020-2060)
0.4
0.2
0.0
−0.2
−0.4
Difference in SPEI


Difference in Mean SPEI for Mongolia (SSP5-8.5 - SSP2-4.5, 2060-2100)
0.4
0.2
0.0
−0.2
−0.4
Difference in SPEI