ASSESSMENT OF POTENTIAL CLIMATE HAZARD IN SWITZERLAND USING LOCAL CLIMATE MODEL

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ABSTRACT

Decision makers are increasingly demanding climate information at the national to local scale in order to address the risk posed by projected climate changes and their anticipated impacts. Readily available climate change projections are provided at global and continental spatial scales for the end of the 21st century. However, they do not fit the needs of sub-national adaptation planning that requires regional or local projections. To fill in these gaps, this study aims to provide reliable information by developing a Regional Climate Model (RCM) for Switzerland using the Statistically Downscaling Method. The objectives of the study are to: 1) develop the RCM based on precipitation and temperature data, 2) assess the reliability of the RCM based on different SSP scenarios using Linear Regression, Cronbach's Alpha, and Probability Density Function, and 3) assess potential climate hazard based on the RCM created and recommend the most suitable SSP scenario for future climate change projection in Switzerland. The result shows that SSP4.5 is the most suitable scenario for future climate projections in Switzerland. The generated RCM provides critical information to support Swiss government, policy makers, and society in developing effective adaptation strategies for climate change. The impacts of increasing temperatures in Switzerland will likely include melting of glaciers and snowpack, leading to changes in water availability for agriculture and drinking water, and increased risk of flash floods and landslides. Further, there will be an increased risk of heatwaves and associated health impacts, and changes in tourism and recreational opportunities. The study contributes to the ongoing efforts to understand and address the complex challenges of climate change.

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APPROVAL SHEET

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SUBMISSION OF THESIS

It is hereby certified that Kathrin Linda Abt (ID No: 22AGM02990) has completed this thesis entitled "ASSESSMENT OF POTENTIAL CLIMATE HAZARD IN SWITZERLAND USING LOCAL CLIMATE MODEL" under the supervision of ChM. Ts. Dr. Tan Kok Weng (Supervisor) from the Department of Environmental Engineering, Faculty of Engineering and Green Technology.

I understand that University will upload softcopy of my thesis in pdf format into UTAR Institutional Repository, which may be made accessible to UTAR community and public.

Yours truly,

Kathrin Abt

Kathrin Abt

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

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Date 28th April 2023

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

CHAPTER 1

INTRODUCTION

When attempting to forecast how future global warming will contribute to climate change, a variety of factors must be taken into account (e.g., amount of future greenhouse gas emission). To simulate the present climate and to predict future climate change, Global Climate Models (GCMs) have been developed (Wayne, 2013; Chokkavarapu and Mandla, 2019). GCMs are regarded as a key resource for examining climate complexity and providing quantitative estimates of future climate change (IPCC, 2001). The demand for accurate and precise future estimates on a local to regional scale is constantly increasing due to the anticipated changes in the global climate system over the 21st century (Fowler, Blenkinsop and Tebaldi, 2007; Maraun *et al.*, 2010).

1.1 Climate Model in Switzerland

Climate models are mathematical representations of key climate-related phenomena. The temperature of the atmosphere and seas, precipitation, winds, clouds, ocean currents, and the extent of sea ice are only a few of the many climate factors that comprehensive GCMs can simulate. The climate models use data from scenarios of GHG and air pollutant emissions and land use trends to provide projections of climate change. Economic and population growth, changes in lifestyle and behaviour, concomitant changes in energy use and land use, technological advancements, and climate policy—all of which are fundamentally uncertain—are the main drivers influencing increases in anthropogenic GHG emissions (IPCC AR5, 2022).

Regional Climate Models (RCMs) have been developed in addition to comprehensive GCMs, which are often reliable at temporal scales of monthly averages and longer. Modern RCMs typically give data with a spatial resolution of between 10 and 50 km. As a result of their increased resolution when compared to GCMs, RCMs are more appropriate for regions with intricate physiographic features. The daily time-series of the RCMs cannot be used directly for local assessments or in climate impact models due to projections at this spatial scale frequently being too coarse and subject to significant biases. Further downscaling is required in order to deliver bias-corrected local climate estimates at daily resolution. Numerous statistical methods have been created in recent years to close the gap between the results of climate models and the local scale (Maraun *et al.*, 2010; Trzaska and Schnarr, 2014; Chokkavarapu and Mandla, 2019). Statistical downscaling is a particularly difficult challenge for locations with complicated topography, such as the Alps, because several local-scale phenomena (such as valley cold pools, convective precipitation, etc.) are not resolved by RCM models (Keller *et al.*, 2017).

The need for trustworthy climate data is expanding throughout Europe as well. Climate model studies of potential effects of climate change on ecosystems have typically relied on GCM projections of future climate (Morales *et al.*, 2007). The following are the main hazards that Europe will face in the future, according to the IPCC AR6 fact sheet: heat-related ecological changes, crop stress from heat and drought, water scarcity, and flooding (Bednar-Friedl, Biesbroek and Schmidt, 2022). With heights ranging from 193 metres to 4634 metres, Switzerland is a country in Central Europe with a climate dominated by mountains and valleys (Presence Switzerland, 2022). In order to examine complex local phenomena linked with climate change in Switzerland, Zubler et al. (2014) highlight the growing need for climate change impact modelling to have more localised climate change scenario information available for both the past and future. Due to Switzerland's location and intricate topography, numerous distinct climate areas have been identified. Given this intricacy, one might anticipate that Switzerland may see significant geographical disparities in the effects of climate change, especially with regard to precipitation patterns (Jasper *et al.*, 2004; Zubler *et al.*, 2014). According to Ceppi et al. (2012), Switzerland has witnessed positive temperature changes over the past 30 years that are approximately 1.6 times larger than the average warming trend in the Northern Hemisphere. This emphasises the significance of reliable information on climate change at regional to local scales, i.e., scales that are most pertinent for end users and decision makers for successful climate adaptation and risk management (Fischer *et al.*, 2012; Zubler *et al.*, 2014).

Given the reasons above, this study aims to downscale climate data to a local scale, which can be used by decision makers and the public to gain an overview over possible climate scenarios in Switzerland and derive adequate decisions from it. The two Shared Socio-Economic Pathways SSP4.5 and SSP8.5 are evaluated in this research using temperature and precipitation data that was statistically downscaled from a Global Climate Model (GCM) to a Regional Climate Model (RCM) using CanESM2. The Canadian Centre for Climate Modelling and Analysis (CCCma) of Environment and Climate Change Canada developed the coupled Canadian Earth System Model (CanESM2), which is now in its second iteration. The IPCC's sixth assessment report (AR6) presents the Shared Socioeconomic Pathways (SSP) as scenarios of anticipated worldwide socioeconomic changes up to 2100. They are applied to create scenarios for greenhouse gas emissions under various climate policies (IPCC AR6, 2022).

Following the Swiss National Basic Climatological Network, the study area is geographical divided into three regions, namely the Jura Mountains (CHJ), the Central Plateau (CHP) and the Swiss Alps (CHA). The historical precipitation data (1991-2021) are retrieved from climate stations and downscaled using the software SDSM. The reliability of the simulated regional climate model will be tested by using reliability statistic, namely Linear Regression, Cronbach's Alpha and Probability Density Function. Figure 1.1 shows the geographical division of the study area.

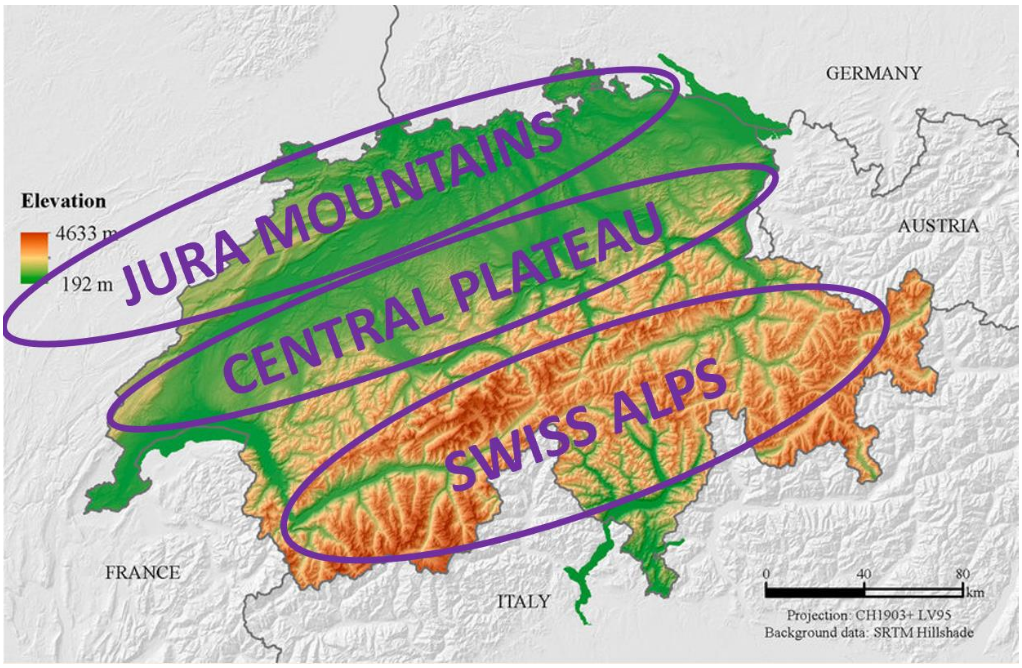

Figure 1.1: Geographical classification of Study Area

1.2 Problem Statement

In order to handle the danger posed by expected climate changes and their anticipated repercussions, decision makers are requesting more and more climate information at the national to local levels. At both the global and continental levels, projections of climate change for the end of the twenty-first century are given (IPCC AR4, 2007). However, sub-national adaptation planning, which calls for regional and/or local predictions of expected conditions in five to ten years, does not match the needs of these projections. The effects of climate change on particular sectors, such as agricultural production, food security, disease prevalence, and population vulnerability, are also of relevance to decision-makers. Numerous impact analyses at the local level—much finer than those at which forecasts were initially made—are performed in response to this need. Frequently, global or continental-scale data are utilised directly to create local-scale impact maps, which is inappropriate because this large-scale data does not take local characteristics into account (Trzaska and Schnarr, 2014; GFDL, 2022).

Process-based models of ecosystem responses are particularly sensitive to fine-scale climate fluctuations, according to the IPCC (2001b), especially in areas with complicated topography and surface cover (like the Alps). The coarse resolution of GCMs, as noted by Morales et al. (2007), is a severe drawback if it is necessary to evaluate the effects of climate change on terrestrial ecosystems at a regional scale. Additionally, impact studies in Switzerland lack high-resolution input data in terms of both time and space, according to Zubler et al. (2014). The development of adaptation methods for hydrology, glaciology, diverse economic sectors such as electricity generation, forestry, agriculture, and tourism, as well as climatic dangers such as heat waves, droughts, flood risks, snowfall levels, and permafrost stability, all depend greatly on the results of impact studies (FOEN, 2012).

Priority must be given to quantifying the amount and intensity of changes in climate variables and their variations for the 21st century in order to close the gaps in temporal and spatial resolution using current scenarios and obtain data to assist decision-makers in achieving the goals set for Switzerland. Therefore, by selecting climate stations in all three distinct geographical regions of Switzerland, statistically downscale it with the known software SDMS and base the study on the recognised SSPs, this study aims to provide reliable information. The paper focuses on the precipitation and temperature (min/max) data.

1.3 Objectives

The objectives of this proposed study are:

1. To develop a Regional Climate Model (RCM) for Switzerland based on precipitation and temperature (min/max) data by using Statistically Downscaling Method.
2. To study the reliability of RCM for Switzerland based on SSP4.5 and SSP8.5 by using Linear Regression, Cronbach's Alpha and Probability Density Function.
3. To assess potential climate hazard based on the RCM created and to recommend the most suitable SSP scenario for future climate change projection of Switzerland.

1.4 Significance of Study

In this study, the potential climate hazard using local climate model in Switzerland is assessed by downscaling observation data. The two data sets used are the precipitation and temperature (min/max) data. The reliability of RCM for climate projection based on two Shared Socioeconomic Pathways (SSP) scenarios is shown. By using the software Statistical Downscaling Model (SDSM), a regional rainfall and temperature assessment for Switzerland will be generated including the SSPs 4.5 and 8.5 climate scenarios of IPCC Fifth Assessment Report (AR5). One SSP scenario will be recommended to serve as an important early warning signal to decision makers and the public.

1.5 Limitations

The The following are crucial things to keep in mind and suggestions to follow when analysing fine-scale data on climate change and its effects There is no guarantee that a model will accurately reflect the future system, even if it can be shown to be a realistic representation of the past system. The future may differ considerably from the past (Wagener, 2022). At local scales, determining climate projections requires several steps. Approximations and assumptions are made at every stage. Climate change estimates and their effects are inherently uncertain. Whether expressly measured or not, they come from a variety of sources and must be remembered (Trzaska and Schnarr, 2014).

The four main sources of uncertainty in climate projections should be briefly mentioned.

1. Uncertainty in future levels of anthropogenic emissions and natural forcings (e.g., volcanic eruptions).
2. Uncertainty linked to imperfect model representation of climate processes.
3. Imperfect knowledge of current climate conditions that serve as a starting point for projections.
4. Difficulty in representing interannual and decadal variability in long-term projections.

It is crucial to convey the uncertainty in climate change estimates and to emphasise that this does not imply that future predictions are illogical or incorrect. Additionally, uncertainty is quantifiable, and judgements can be taken despite it. However, while applying the information, Users must take these uncertainties into account (Trzaska and Schnarr, 2014).

CHAPTER 2

LITERATURE REVIEW

2.1 Climate Models

To understand the current climate and the behaviour of the climate in the future, climate models are the main tools that provide reasonably accurate information on the climate at the global, hemispheric, and continental scales. Models assess how much of the observed climate changes may be a result of anthropogenic activity, natural variability, or both. Their findings and estimates offer crucial data to better inform choices affecting the management of water resources, agriculture, transportation, and urban development at the federal, state, and municipal levels (Trzaska and Schnarr, 2014; GFDL, 2022).

Equations are used in climate models to reflect the interactions and processes that shape the planet's climate. By using thousands of distinct factors over hourly, daily, and monthly timescales, it is feasible to create a fairly full picture of the Earth's climate. These results include the temperature and humidity of the atmosphere's various layers, from the surface to the upper stratosphere, as well as the temperature, salinity, and pH of the seas, from the surface to the ocean floor. Estimates of snowfall, rainfall, snow cover, and the size of glaciers, ice sheets, and sea ice are also produced using models. They produce climate phenomena like the jet stream and ocean currents as well as wind speed, strength, and direction (Mcsweeney and Hausfather, 2018).

Global environment Models (GCMs) have been built to model the current environment and forecast future climate change (Chokkavarapu and Mandla, 2019). GCMs are regarded as a key resource for examining climate complexity and providing quantitative estimates of future climate change (IPCC, 2001). A complicated mathematical depiction of the four main parts of the climate system—atmosphere, land surface, ocean, and sea ice—and their interactions is known as a global climate model, sometimes known as a general circulation model. GCM record heat transfer as well as air and water fluxes in the atmosphere and/or oceans. They mimic the mechanics of the climate itself in this way. Following are the key elements of the climate system that need to be understood (Trzaska and Schnarr, 2014; GFDL, 2022; IPCC AR6, 2022).

- The atmospheric element, which models clouds and aerosols and is crucial in the global transportation of heat and water.
- The land surface component, which mimics features like vegetation, snow cover, soil water, rivers, and carbon storage on the surface.
- The ocean component, as the ocean is the main source of heat and carbon in the climate system, and the biogeochemistry, which mimics current movement and mixing.
- The sea ice element, which controls the absorption of solar radiation and the flow of heat and water between the air and the sea.

A model cannot possible simulate all these processes for each cubic metre of the climate system due to the complexity of the climate system and computing resource limitations. Instead, a three-dimensional grid of cells reflecting distinct geographic areas and altitudes is used in climate models to partition the earth. On the global grid, equations have been calculated for a set of climate variables, such as temperature, for each of the components (atmosphere, land surface, ocean, and sea ice). The various elements exchange heat, water, and momentum fluxes while also computing how they are changing over time. They work as a linked system to interact with one another. Each homogeneous grid cell in a model is one where there is just one value of a particular variable (Trzaska and Schnarr, 2014; Mcsweeney and Hausfather, 2018; GFDL, 2022). Figure 2.1 below shows an illustration of a GCM.

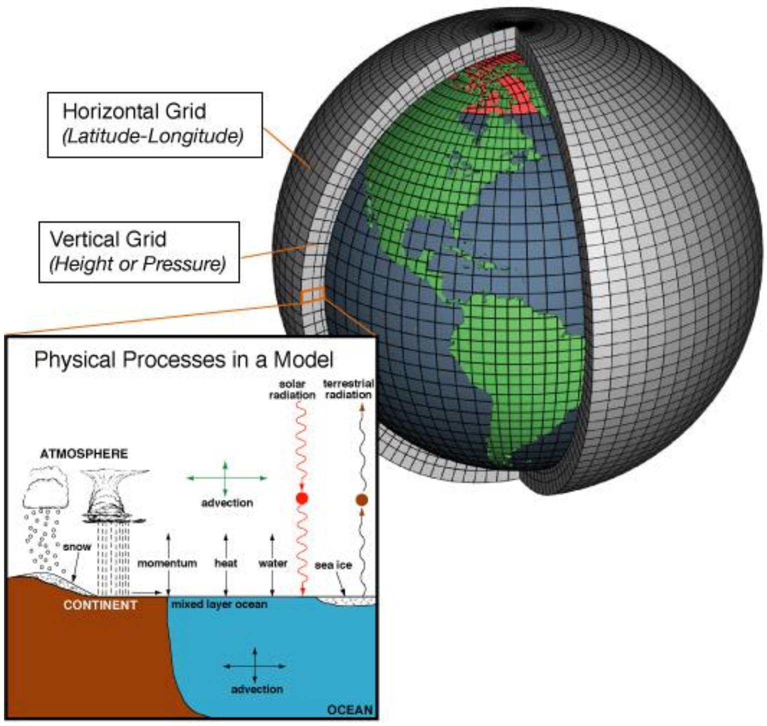

Figure 2.1: Conceptual Structure of a GCM (NOAA), 2012)

The outputs of GCMs have a coarse resolution (grid-cell resolutions of roughly 250–600 km) and offer quantitative projections of upcoming climate change that are accurate at the continental and global scales and over lengthy time periods (monthly averages and longer) (Mearns *et al.*, 2003; Trzaska and Schnarr, 2014). GCMs do not accurately define local phenomenon and therefore not suitable for assessing impacts precisely at the local level. One method of "downscaling" global climate information to a local scale is through the use of so-called Regional Climate Models (RCMs). This entails applying data from a GCM or coarse-scale observations to a particular location or region (Neelin, 2010). The information can be delivered at fine, sub-GCM grid scales, which are better suited for investigations of regional phenomena, by downscaling the outcome of a GCM. RCM essentially perform the same function as GCMs, albeit for a smaller portion of the Earth. RCMs can typically be done more rapidly and with a higher resolution than GCMs because they cover a smaller area. Since the grid cells in a model with a high resolution are smaller, it can produce climate data for a particular location in more detail (Mearns *et al.*, 2003; Field *et al.*, 2014; Soro *et al.*, 2017; Chokkavarapu and Mandla, 2019; Giorgi, 2019). RCM outputs have a smaller resolution (grid-cell resolutions of approximately 10–50 km) and are more appropriate for regions with complicated physiographic traits (Keller *et al.*, 2017; Chokkavarapu and Mandla, 2019). The process from a GCM to an RCM is illustrated below in Figure 2.2.

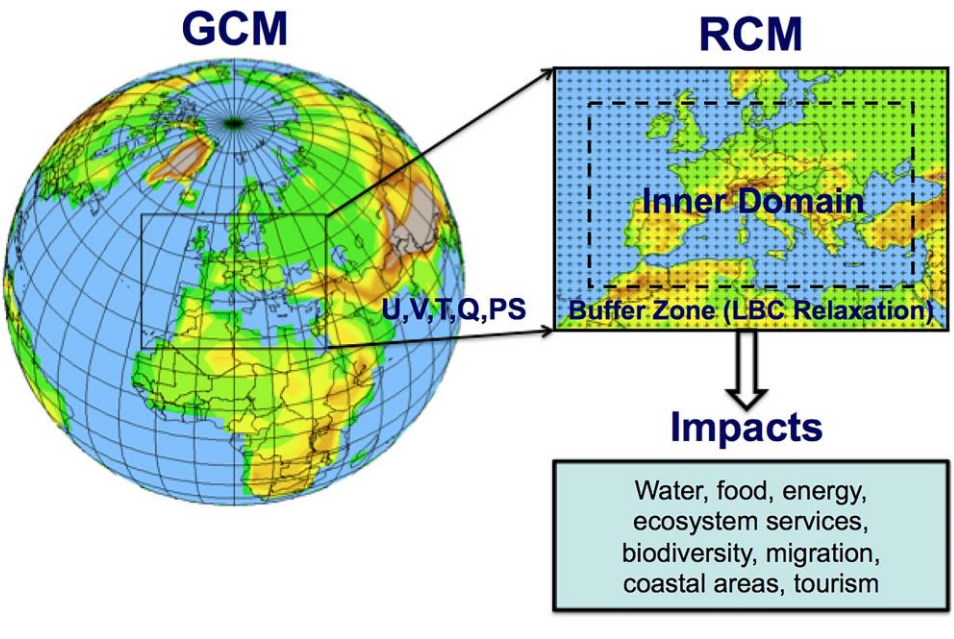

Figure 2.2: Schematic depiction of regional climate modelling (Giorgi, 2019)

2.2 Statistical Downscaling

Given the previous mentioned reasons for the necessity for climate models for smaller regions, downscaling techniques that can translate global projections to regional or local spatial scales have come to the forefront, offering therefore practical products that represent the local features of relevance. The statistical and dynamical approaches are the two basic methods for downscaling climatic data (Feyissa *et al.*, 2018; Manzanas *et al.*, 2018).

Dynamic downscaling is based on regional models, which are initialised and driven at the boundaries by the coarse global model outputs. These models operate on a relatively narrow grid (e.g. 10-20 km) over a constrained domain (e.g. Europe). These models can produce regional projections for a variety of climate variables, but they may still have major biases that must be corrected in post-processing before being applied to impact applications (Yoon, Ruby Leung and Correia, 2012; Manzanas *et al.*, 2018). Other than that, dynamic downscaling also regenerates local climates by physical principles. The application of this approach is seen as computationally intensive and expensive (Ribalaygua *et al.*, 2013).

Statistical downscaling is based on empirical correlations derived from reanalysis or from global seasonal forecasting systems between a local observable predictand of interest (such as temperature or precipitation) and one or more relevant model predictors. In other words, developing the statistical relationship between local climatic variables and broad predictors is a part of statistical downscaling (Ribalaygua *et al.*, 2013; Manzanas *et al.*, 2018).

Statistical downscaling has established approved and validated statistical methods. It can directly incorporate the local observational record and is computationally cheap. The ensembles of climatic scenarios enable risk or uncertainty calculations by employing statistical downscaling. In addition, it is more adaptable than dynamic downscaling. Additionally, this explains why dynamic downscaling is rarely used to create ensembles of climate scenarios (Ribalaygua *et al.*, 2013; Wilby and Dawson, 2013).

A free tool that generates high resolution climate change scenarios is the Statistical Downscaling Model (SDSM). The software determines statistical correlations between global climate variables (the predictors) and local climate variables (the predictand) using a variety of linear regression approaches. The SDSM programme handles operations such as data transformation and quality control, model calibration, variable screening, frequency analysis, statistical analysis, scenario creation, and charting of climate data. Extreme temperature ranges, seasonal precipitation totals, and the behaviour of inter- and intra-site precipitation are all accurately estimated by the SDSM. With the help of this open-source software, climate change time series may be created in locations where there are enough daily data for model calibration and archived GCM output to create scenarios for the twenty-first century (Wilby and Dawson, 2013; Feyissa *et al.,* 2018). The SDSM produces accurate estimates of extreme temperatures, seasonal precipitation totals, and regional and inter-site precipitation behaviour, according to numerous studies (Wilby and Dawson, 2013; Samuale, Raj and Girmay, 2014; Abbasnia and Toros, 2016).

It should be pointed out to end users that the downscaling process results in climate information at scales finer than the original projections and requires additional information, data, and assumptions. As a result, the results are subject to additional uncertainties and limitations (Trzaska and Schnarr, 2014).

2.3 Shared Socioeconomic Pathways

Future societal growth and development, which are metrics influenced by a number of factors, including international cooperation on greenhouse gas reductions, political will, and technology breakthroughs, will have a significant impact on how much the climate changes. Therefore, it is best practise to offer practitioners a variety of future climate change scenarios that take varying levels of greenhouse gas emissions into account rather than a single set of future climate data. An international team of climate scientists, economists, and modelers of energy systems have developed a number of new scenarios (sometimes referred to as "pathways") that look at how global culture, demographics, and economics may change over the course of the next century. Shared Socioeconomic Pathways (SSP), as they are known, are crucial inputs for the most recent climate models. The SSP is a collection of five narratives that explore several paths for human advancement and planetary environmental change in the twenty-first century. They can be applied to climate studies in the upcoming years and serve as the foundation for climate models (O'Neill *et al.*, 2017; van Vuuren *et al.*, 2017; Hausfather, 2018; Climatedata, 2022).

The SSPs five scenarios are:

- Sustainable development (SSP1)
- Middle-of-the-road development (SSP2)
- Regional rivalry (SSP3)
- Inequality (SSP4)
- Fossil-fuelled development (SSP5)

The two broad categories of barriers to mitigation and challenges to adaptation can be used to group the five tales (see Figure 2.3). Low obstacles exist for both adaptation and mitigation in SSP1 (Sustainability). In this case, policies prioritise protecting the environment, developing sustainable energy sources, and promoting human well-being. SSP3 (Regional Rivalry), in contrast, is characterised by significant obstacles to both mitigation and adaptation. In this situation, nationalism directs policy and regional and local issues are prioritised over global ones. The other SSPs "fill out the spectrum" of potential futures. High obstacles to adaptation and low challenges to mitigation characterise SSP4 (Inequality), high challenges to mitigation and low challenges to adaptation characterise SSP5 (Fossil-fueled Development), while middle of the road (SSP2) represents moderate challenges to both mitigation and adaptation (O'Neill *et al.*, 2017; Climatedata, 2022).

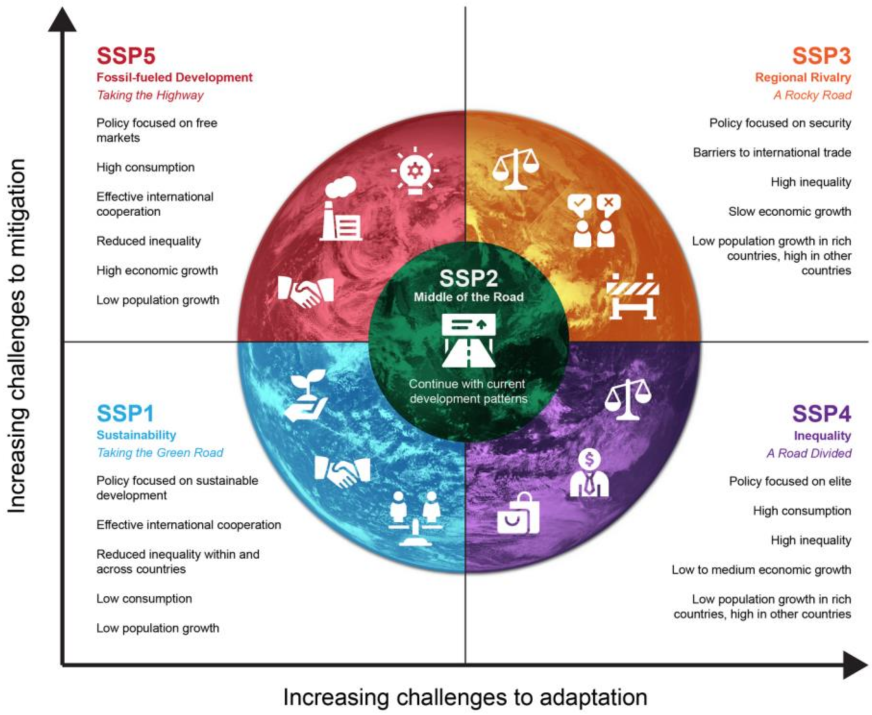

Figure 2.3: Five shared socioeconomic pathways (SSPs) (Climatedata, 2022)

Representative Concentration Pathways, or RCPs, the earlier greenhouse gas concentration scenarios, are further improved by SSP-based scenarios. RCPs were specifically created for the community of climate modellers to investigate the effects of various emission paths or emissions concentrations (Climatedata, 2022). Following, an overview over the RCPs is given with a more detailed explanation on RCP4.5 and RCP8.5 (which now are rebranded to SSP4.5

and SSP8.5), which are the scenarios chosen for this study.

The (RCPs) are a collection of four paths created for the community of climate modellers as a foundation for the examination of long-term and short-term modelling scenarios (van Vuuren *et al.*, 2011). These RCPs were provided as future warming scenarios in the IPCC's fifth assessment report (AR5) (IPCC AR5, 2022). The RCPs provide four distinct trajectories for land use, air pollutant emissions, and greenhouse gas (GHG) emissions in the twenty-first century (see Figure 2.4). Basically, depending on how high the GHG concentration will be in the coming years, the various paths represent various situations. A strict mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and a scenario with extremely high GHG emissions are all included in the RCPs (RCP8.5) (IPCC AR5, 2022).

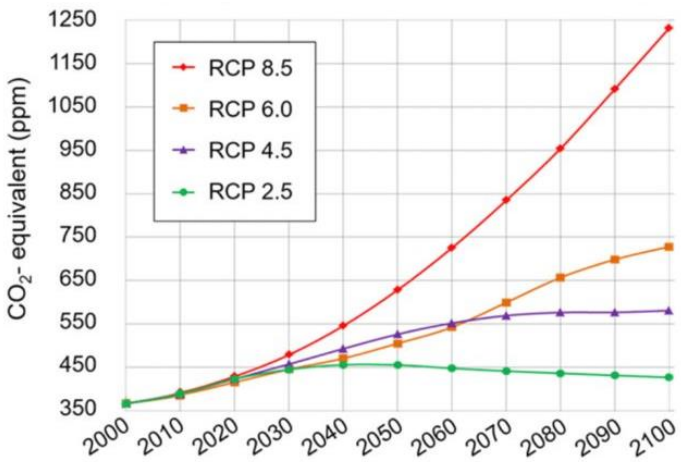

Figure 2.4: The four Greenhouse Gas Concentration Pathways (IPCC AR5, 2022)

Radiative forcing is stabilised at 4.5 W m2 in the year 2100 under the RCP4.5 scenario, never rising above that level. The need to reduce emissions in order to meet this goal has led to changes in the energy system, such as a move towards electricity, the use of energy sources with lower emissions, and the introduction of carbon capture and geologic storage technology. In order to meet the objective of limiting emissions and radiative forcing, RCP4.5, which is a stabilisation scenario, implies that climate policies would be implemented, in this case the implementation of a set of global greenhouse gas emissions prices (Thomson *et al.*, 2011; van

Vuuren *et al.*, 2011).

RCP8.5 is sometimes referred to as the "business-as-usual" scenario, which means that unless humankind takes action to reduce emissions, this scenario with the greatest emissions will take place (van Vuuren et al., 2011). The rapid advancement of renewable energy technology and the emergence of climate legislation, according to Hausfather and Peters (2020), have made it far less likely that emissions will reach the level set by RCP8.5 since 2011, when the RCPs were first established. Nevertheless, emission trends in developing nations follow RCP8.5, and high land-use emissions may indicate that emissions will do so even at the global level in the future (Pedersen *et al.*, 2020). Other factors resulting in high emissions include higher population or economic growth or rapid development of new energy services. Climate projections of RCP8.5 can also result from strong feedbacks of climate change on (natural) emission sources and high climate sensitivity and therefore their median climate impacts might also materialise while following a lower emission path (IPCC AR6, 2022).

RCP4.5 and RCP8.5 are translated into the SSP narratives SSP 2-4.5 and SSP 5-8.5 (Climatedata, 2022). For a better understanding, the designations SSP4.5 and SSP8.5 are used in this study.

2.4 Reliability Tests

It is crucial and necessary to validate results that have been downscaled (based on historical data) in order to draw attention to systemic biases and the limitations of the data. When a measurement is repeated numerous times, the scale's reliability is measured by how consistently accurate the results are. By figuring out the correlation between the results received from several scales, one may figure out the reliability test by figuring out the percentage of system changes in the scale. Since the scale will generate consistent findings, it is dependable if the reliability test's correlation is high. Three reliability assessments, including linear regression, Pearson correlation, Cronbach's alpha, and probability density function, will be carried out in this study. While reliability measure - Cronbach alpha represents the consistency between observation data and SSP scenarios, linear regression and Pearson correlation reflect the association between observations data and SSP scenarios. A probability distribution for a random, continuous variable is described by the probability density function (PDF) (Hryniewicz and Karpinski, 2014; Trzaska and Schnarr, 2014; Goforth, 2015; Mahamad, 2015).

2.4.1 Linear Regression

A common technique is simple linear regression, which establishes a linear relationship between a local predictand, such as local-scale temperature, and a large-scale atmospheric predictor, such as GCM-simulated temperature, represented in the equation below as x and y, respectively (Trzaska and Schnarr, 2014). Mahamad (2015) tests the dependability using linear regression and provides a numerical example of the study using three variables: maximum temperature, minimum temperature, and rainfall. The model is constructed using the linear regression, which describes the relationships between the variables. Given the link between both X and Y, a simple regression model of X and Y is shown as follows. In a linear regression, Y is the dependent variable and X is the independent variable (Trzaska and Schnarr, 2014):

$$Y = \alpha + \beta X$$

Where:

Y = dependent variable

X = independent variable

α = Regression coefficients

β = Regression coefficients

Because it will be similar to a mathematical equation of slope and intercept line, we will perform simple linear regression by calculating slope and intercept. The regression coefficient formula can be used to calculate the magnitude and direction of the association between the two variables. The mathematical and statistical evolution processing can also make use of a variety of correlation coefficient formulas.

Sreehari and Ghantasala (2019) shows in their study on the prediction of climate change that the regression coefficient formula, which is provided below, can be used to assess the magnitude and direction of the link between the two variables. The coefficient determination gauges how well the regression line can depict the data. The link between the dependent and independent variables can be defined in terms of its strength and direction.

$$r = \frac{\sum(x_i-\bar{x})(y_i-\bar{y})}{\sum(x_i-\bar{x})^2}$$

Another author utilized linear regression to assess the global warming. The coefficient of determination (R-squared) is used as a measure of the usefulness of the regression model (Marzouk, 2021).

2.4.2 Cronbach's Alpha

Cronbach's alpha is a measure used to assess the reliability, or internal consistency, of a set of scale or test items. The formula is as follows:

$$r = \frac{rk}{(1 + (k - 1)\,r)}$$

Where:

k = the number of items to be considered

r = the average correlation between item

Cronbach's alpha, can be interpreted by alpha coefficient from ranges 0 to 1 (see Table 2.1). Values > 60 can be seen as reliable and values > 0.8 as very reliable. It may give negative value as well, which means that something is wrong with the data (Goforth, 2015; Ahdika, 2021).

Table 2.1: Cronbach's Alpha Level of Reliability

Alpha Score	**Level of Reliability**
0.0 – 0.2	Less Reliable
0.2 – 0.4	Rather Reliable
0.4 – 0.6	Quite Reliable
0.6 – 0.8	Reliable
0.8 – 1.0	Very Reliable

Tan and Oishi (2021) used Cronbach's Alpha in their study developing a regional climate model for Japan to state which of the two SSP they analysed is more reliable. Setiono *et al.* (2016) showed with Cronbach's Alpha that their simulated rainfall data is reliable and consisted.

2.4.3 Probability Density Function

Among statistical parameters, the Probability Density Function (PDF) is well-known. For a continuous, random variable, a probability density function represents the probability distribution. How likely it is that an observed value actually occurred is shown by the form of the PDF. A frequent example that can be explained using only its mean and standard deviation is the normal distribution. The mean of a PDF—which is defined as the arithmetic average value—is frequently used to describe PDFs.

The calculation for the PDF of the normal distribution is as follows:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

Where:

x = value of the variable or data being examined

μ = mean

σ = Standard deviation

(Kenton, 2022).

2.5 Spatial Analysis (QGIS)

The number of rain stations used in the study determines how accurately the amount of precipitation is measured. Since there are four stations included in this study, it is advised to perform a spatial analysis and produce a rainfall map. The spatial interpolation approach can be used to map the rainfall data for a study region because there is a geographic correlation between the amounts of rainfall in different areas. It is possible to consider the validity of rainfall maps produced using single and mixed spatial interpolation methods to be high. The software QGIS creates rainfall maps that assist in estimating values at additional study area unknown sites, resulting in improved annual rainfall images (Pillai and Ashna, 2015; Satish, Rangarajan and Thattai, 2019).

CHAPTER 3

METHODOLGY

The methodology for the proposed study is discussed in this chapter, starting with a flowchart showing the summary of the whole project flow (Figure 3.1).

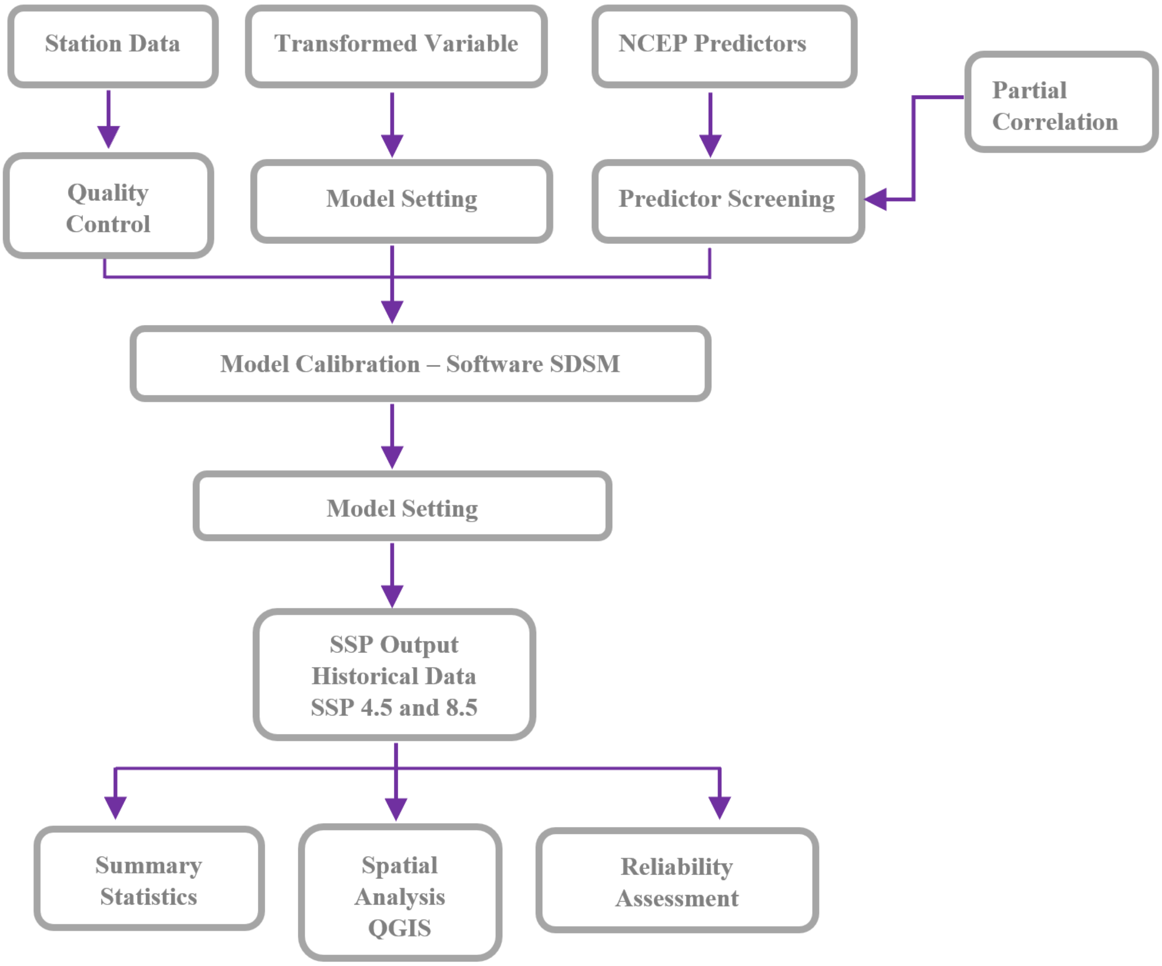

Figure 3.1: Study Workflow

3.1 Description of the Study Area

The latitude and longitude of Switzerland are 46.8182° N and 8.2275° E, respectively. The nation is situated in both the northern and eastern halves of the world. Switzerland is a country in Central Europe with elevations ranging from 193 metres to 4634 metres with a climate dominated by mountains and valleys. Switzerland is totally enclosed by land. There are currently about 8.5 million people living there, and the population is rising. The Alps, the Central Plateau, and the Jura are the three main geographic regions that make up its 41,285 km^2 surface area. About 58% of the nation is made up of the Alps, 31% is the Central Plateau, and 11% is the Jura. These geographic locations form the basis for the study areas: Central Plateau (CHP), Jura Mountains (CHJ), and the: Jura Mountains (CHJ), Central Plateau (CHP) and the Swiss Alps (CHA) (Presence Switzerland, 2022; World Population Review, 2022).

The nation features 49 mountain peaks with a height of 4,000 metres or above, or "four-thousanders." Only 11% of the population resides within the Alps, which make up the majority of the country. 7.5% of Switzerland's land is occupied by settlements. Among them are regions dedicated to housing, infrastructure (trade, industry, and transportation), water and energy supply, wastewater disposal, as well as parks and other outdoor places. 30% of the land in Switzerland is covered with forest and woods, whereas about 40% is used for agriculture. On former mountain pastures, a large portion of Switzerland's natural forest regrowth has taken place. An estimated 1,500 lakes make up 4% of Switzerland's total geographical area, together with other bodies of water including streams and lakes. Four major rivers in Switzerland – including the Rhine, Rhone, Reuss and Ticino – are in the Gotthard massif, in the heart of the Swiss Alps. The country has 6% of Europe's freshwater reserves. The source of major European rivers like the Rhone, Rhine and Inn is in the Swiss Alps (Presence Switzerland, 2022; World Population Review, 2022).

With major regional and altitude variations, Switzerland has a predominantly continental climate. The Central Plateau has a continental climate that is largely humid. There is a sizable portion of the north that has an oceanic climate. The south-central region's tiny area has a humid subtropical climate. The subarctic foothills of the Alps have frigid winters and cool summers. The Alps have an alpine climate above the tree line. The Alps and temperate latitudes have the biggest effects on the climate. Depending on the geography and altitude, summers in Switzerland range from cold to warm and humid. In the summer, it is possible but only for brief times to experience temperatures above 30°C. Compared to winter, summer is rainier. Winters are chilly and dry. The temperatures are freezing between December and March. The average temperature in the Plateau is 8.9°C. In the winter, the Jura and the Alps are covered in snow and extremely cold. While the Alps get snow even in the early summer, the Central Plateau only gets snow on occasion in spring. The climate is not exactly predictable and the weather is typically unpredictable. It also varies from year to year. All through the year, the Fohn winds blow, bringing with them warmth. The chilly Bise winds, which originate in the northeast, generally blow in the winter and spring. The country's wettest regions are the High Alps and Ticino, the southernmost canton. In Switzerland, there is a lot of yearly precipitation, ranging from 812 mm to 2387 mm. Rainfall occurs all year long. The wettest time of year is in the summer. The driest season is from late October to early spring. Between 812 mm and 1320 mm of precipitation fall on the Central Plateau each year. Between 1219 and 1625 millimetres fall on the Jura and the foothills of the Alps, while up to 2489 millimetres reach the High Alps. The Plateau and foothills receive between 508 mm and 1524 mm of snow each year. Snowfall in the High Alps and the Jura Mountains ranges from 2540 mm to 5080 mm annually. In Säntis, the biggest yearly snowfall totals can reach 11'125 mm (Weather Atlas, 2022).

Natural weather dangers like floods, landslides, rock falls, avalanches, and storms frequently occur in Switzerland. Despite their rarity, earthquakes do carry some risk. Summertime can occasionally see forest fires. In the spring and summer, floods can be dangerous. The water levels in streams and rivers significantly increase as a result of the snowmelt in the spring. Summertime is when thunderstorms are most common, especially in the high mountains. Snowstorms frequently occur in the upper mountains throughout the winter (Weather Atlas, 2022).

3.2 Data Collection

3.2.1 Observation Data

First of all, the observation data is obtained from the Federal Office of Meteorology and Climatology Switzerland (also called "MeteoSwiss"), providing high-quality homogenized daily precipitation and minimum and maximum temperature (MeteoSwiss, 2022). The data of MeteoSwiss is collected from the Swiss National Basic Climatological Network (NBCN). Four different stations were selected, based on the recommendation of the NBCN (2022), each reflecting a distinct climate region in Switzerland. Care was taken to ensure a spatially sensible distribution of the various sites within Switzerland across all climatic regions and altitudes. For instance, the stations cover a wide range of altitudes from 250 m a.s.l. (Lugano) up to 2500 m a.s.l. (Säntis). The detail information of the station represents Switzerland and the specific location are shown in Table 3.1 and Figure 3.2, respectively. The data of the last 30 years are considered (period 1991-2021) as this is the usual period to obtain meaningful statements about the climate. Therefore, the daily values are obtained from 01/01/1991 to 31/12/2021. An order inventory from Federal Office of Meteorology and Climatology Switzerland can be found in Appendix A.

Table 3.1: Information of selected Stations (MeteoSwiss, 2022)

Nr	Station	Abbr	Record Period (30 years)	Measurement height (m a. sea level)	Latitude / Longitude	Coordinates (CH)	Study Area
1	Bern	BER	1991-2021	553	46.990744 / 7.464061	2601934 / 1204410	CHJ
2	Säntis	SAE	1991-2021	2'501	47.249447 / 9.343469	2744188 / 1234920	CHP
3	S. Bernardino	SBE	1991-2021	1’639	46.463542 / 9.1847	2734116 / 1147294	CHA
4	Lugano	LUG	1991-2021	273	46.004217 / 8.960322	2717874 / 1095883	CHA

Figure 3.1: Locations of the four selected Stations (World Atlas, 2022)

Bern is the capital city of Switzerland and is located in the central part of the country, on the Swiss plateau. The city has a humid continental climate, which is characterized by relatively warm summers and cold winters. Säntis is a mountain peak located in the eastern part of Switzerland. It is situated in the Alpstein range of the Appenzell Alps, at an altitude of 2,502 meters above sea level. S. Bernardino is a small village located in the southern part of Switzerland, in the canton of Graubünden. It is situated in the Alps, at an altitude of around 1,680 meters above sea level, and has an alpine climate. Lugano is a city located in the southern part of Switzerland, in the Italian-speaking canton of Ticino. It is situated on the shore of Lake Lugano, surrounded by mountains, and has a subtropical climate.

3.2.2 Predictor CMIP6

In this study, the predictors from the CMIP6 ensemble are used. CMIP Phase 6 (i.e., Coupled Model Intercomparison Project) is a coordinated international effort to improve understanding and modeling of the Earth's climate system. It includes a set of standardized experiments designed to compare climate model simulations from different modeling groups worldwide. The focus of CMIP6 is to study the historical climate and to project the future climate under different scenarios of greenhouse gas emissions. Therefore, the predictors are considered suitable for this study. CMIP6 is coordinated by the World Climate Research Program (WCRP). CMIP6 (as of 2022) is the most recent version of climate models and the outputs are used in the IPCC’s sixth assessment report (Ocean Health Index, 2022).

CMIP6 divides the globe into grid cells and determines the values of the predictors determined for each grid cell. This makes it possible to obtain the data for specific locations. To obtain the predictor values for the target area, the coordinates can be entered on the website. In order to cover the four stations in Switzerland, following grid cell box is required: Box_4X_49Y (see [CMIP6 ensemble of daily predictor variables]) (Government of Canada, 2022). The necessary cell is downloaded from the website and the files unzipped. The folder contains various subfolders, not all of which are needed for this work. Figure 3.3 shows a screenshot of the downloaded data. Predictor variables from the National Centre for Environmental Prediction (NCEP) are included in one subfolder and used as predictors (File name: NCEP-DOE_1979-2014).

NCEP is a U.S. government agency responsible for generating weather forecasts and climate predictions. NCEP has developed several atmospheric reanalysis datasets, such as the NCEP-NCAR reanalysis and the NCEP-DOE reanalysis, which are widely used in climate research. In this study, the second mentioned NCEP-DOE reanalysis is used. The NCEP-DOE (National Centers for Environmental Prediction-Department of Energy) Reanalysis is a comprehensive dataset that provides a long-term record of global atmospheric and land-surface conditions. The reanalysis combines observational data with a numerical weather prediction model to generate a continuous 55-year dataset of global atmospheric conditions, including temperature, humidity, wind, and pressure, as well as surface conditions such as snow cover and soil moisture. The NCEP data provides 23 daily predictor variables which can be used for statistical downscaling. The predictors are listed in Table 3.2 and the application of these predictors is described in the next chapter.

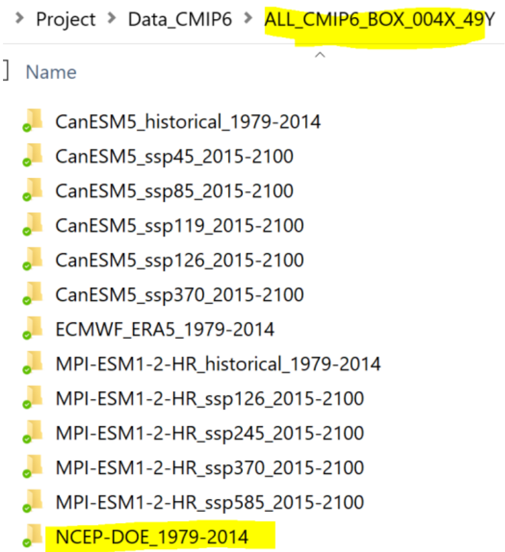

Figure 3.2: Downloaded CMIP6 Data for Box 004X-49Y

Table 3.2: The 23 predictor variables (Duan and Mei, 2014; CMIP6, 2022).

Nr	Abbr	Description	Unit	Nr	Abbr	Description	Unit
1	mslp	Mean sea level pressure	Pa	13	p8_f	850 hPa airflow strength	Pa
2	p_f	Surface airflow strength	Pa	14	p8_u	850 hPa zonal velocity	m/s
3	p_u	Surface zonal velocity	m/s	15	p8_v	850 hPa meridional velocity	m/s
4	p_v	Surface meridional velocity	m/s	16	p8_z	850 hPa vorticity	s^{-1}
5	p_z	Surface vorticity	s^{-1}	17	p850	850 hPa geopotential height	m
6	p_zh	Surface divergence	s^{-1}	18	p8zh	850 hPa divergence	s^{-1}
7	p5_f	500 hPa airflow strength	Pa	19	prcp	Total precipitation	%
8	p5_u	500 hPa zonal velocity	m/s	20	s500	500 hPa specific humidity	%
9	p5_v	500 hPa meridional velocity	m/s	21	s850	850 hPa specific humidity	%
10	p5_z	500 hPa vorticity	s^{-1}	22	shum	Surface specific humidity	kg/kg
11	p500	500 hPa geopotential height	m	23	temp	Near-surface temperature	K
12	p5zh	500 hPa divergence	s^{-1}				

3.3 Predictor Screening

Since the present project focuses on the time period 1991-2021, the historical data from 1991 to 2014 are used to conduct the predictor screening, so that they match the selected time period. As described in the previous chapter, the data from the NCEP-DOE reanalysis is used. A predictor screening is done because it is not representative to use all the predictors. The screening is executed in SPSS Statistics 25. For all the four climate stations correlations (Pearson test) and factor (principal component) analyses are conducted (see Appendix B). This means that the 23 predictors are each correlated with a data set from a weather station (precipitation, temperature max, temperature min). The values obtained are scanned for the most significant one. In this case, the level of significance varies from -1 to 1. A higher value indicates a higher significance (independent of the sign). Therefore, the predictors with a high value are selected. For each dataset or analysis, 4 to 5 predictors were selected. The results show that the factor analysis reached higher values, therefore the downscaling will be done based on the selected predictors of the factor analysis.

Of the 23 predictors, most of the same showed the most significant result. This is not surprising, since the 4 climate stations are close to each other, since Switzerland is a small country. For example, the station SAE and BER are only 130 km apart. Following in Table 3.3 an overview over the four most used predictors is shown.

Table 3.3: Major predictors for this study

Abbr	**Description**	**Unit**
s500	500 hPa specific humidity*	%
s850	850 hPa specific humidity*	%
shum	Surface specific humidity*	kg/kg
temp	Near-surface temperature	K

** The specific humidity is defined as the ratio of the mass of water vapor to the total mass of atmospheric gases.*

Table 3.3 shows that the specific humidity at 500 hPa and 850 hPa, the surface specific humidity and the near-surface temperature are the major controlling parameters for both the daily maximum and minimum temperatures as well as the precipitation for the four selected climate stations.

3.4 Software

Through the whole statistical experimental of this study, the three main software that required to complete the project are Statistical Downscaling Model SDSM, SPSS Statistics 25 and Microsoft Excel 365. The Statistical Downscaling Model (SDSM) software is used to generate climate models by statistically downscaling Global Climate Model (GCM) outputs to a finer spatial resolution and generating daily or sub-daily time series of meteorological variables using historical observations, which can then be used to simulate future climate scenarios at a local or regional scale. Statistical downscaling and the generation of the historical model and the SSP4.5 and SSP8.5 models are performed in SDSM Version 4.2.9. SPSS Statistics 25 is used to carry out the predictor screening as well as conducting the reliability tests after the downscaling process. Microsoft Excel 365 is required to calculate the monthly data and to complete the climate models.

3.5 Statistical Downscaling

As already mentioned in the theory section, SDSM (Statistical Downscaling Model) is a statistical model that is used to downscale large-scale climate variables, such as temperature and precipitation, to local scales. The steps that are carried out in the SDSM are explained below. In order to make the process comprehensible and understandable for the reader, general explanations are given on the one hand and on the other hand the concrete individual files/steps for the project at hand are listed. Screenshots of SDSM can be found in the Appendix C. Before the description begins, a short overview of the project to show the initial situation once again. The project includes data from four climate stations in Switzerland across all climatic regions and altitudes. For each of the four station, three data sets were collected (daily value):

- Precipitation
- Temperature maximum
- Temperature minimum

Using the datasets and predictors, scenario files are now to be created. First, historical models are generated. The historical models are generated to validate the application of the predictors. After the historical scenario models have been generated, they are compared with the observation data in a next step. This step is also performed in SDSM. If the two datasets match, the generated scenarios can be considered appropriate to predict the future climate. If there are deviations, a bias correction is applied before proceeding with the data. Once the data has been cleaned, the future climate scenario files can be created (SSP4.5 and SSP8.5).

Before the data observation data, which are obtained from the Federal Office of Meteorology and Climatology Switzerland, are processed in SDSM, a quality control is performed. This is to ensure that the data set is complete and free from errors. All data files are reviewed for completeness and appropriateness. After the quality control, data transformation is performed in SPSS. This is necessary to have the data in the right format to be processed in SDSM.

1) Calibration files

In statistical downscaling, calibration files are the input files used to train the statistical model. Calibration files typically include historical data on large-scale atmospheric variables such as temperature and precipitation. To generate the calibration files, the observation files with the daily values from 1991 to 2021 are used as input files. Predictor variables in SDSM are additional variables that are used to improve the model's performance by capturing more of the variability in the local-scale climate variable that is being downscaled. Predictor variables from the National Centre for Environmental Prediction (NCEP) including the time period 1991 to 2014 were used. The data was included in the downloaded CMIP6 data for the location Switzerland (grid cell box: Box_4X_49Y). In advance, the predictors variables were screened in order to filter out the 3 to 4 most significant ones (see Appendix B). These are now coupled with the observation data in order to obtain an accurate and reliable output file. The output files equal the calibration files.

2) **Scenario files**

Scenario generation in SDSM refers to the process of using the calibration files to generate projections of local-scale climate variables under different future scenarios of climate change. The calibration files generated in the first step serve as input files. Besides, GMC Directory data are included to create the scenario files. GCM Directory is a term that refers to a collection of Global Climate Model (GCM) data files. These are used as input to statistical downscaling models such as SDSM and typically contains a range of variables, such as precipitation and temperature. These variables are used as inputs to scenario file generation and help to downscale the large-scale climate variables to a finer spatial resolution that is more relevant to local-scale climate variables. In this project, CanESM5 predictors were used. As reminder, CanESM5 (Canadian Earth System Model version 5) is a global climate model that simulates the Earth's climate system. CanESM5 is one of the state-of-the-art global climate models that have been used in the latest IPCC (Intergovernmental Panel on Climate Change) reports to project future climate change under different greenhouse gas emission scenarios. The output file is thus obtained from the calibration file (input file) using CanESM5 predictors (GCM Directory). The output files equal the scenario files meaning the output are the generated scenarios. The scenario generation can be seen as simulation of daily precipitation or temperature data series with both observed (Federal Office of Meteorology and Climatology Switzerland) and modelled (CanESM2) data. For the scenario generation of the historical model and climate models different predictors are used. Figure 3.4 shows the downloaded data.

- **Historical models:** CanESM5 historical (data from 1979-2014)
- **Climate Models based on SSP4.5:** CanESM5_ssp245 (data from 2015-2100)
- **Climate Models based on SSP8.5**: CanESM5_ssp585 (data from 2015-2100)

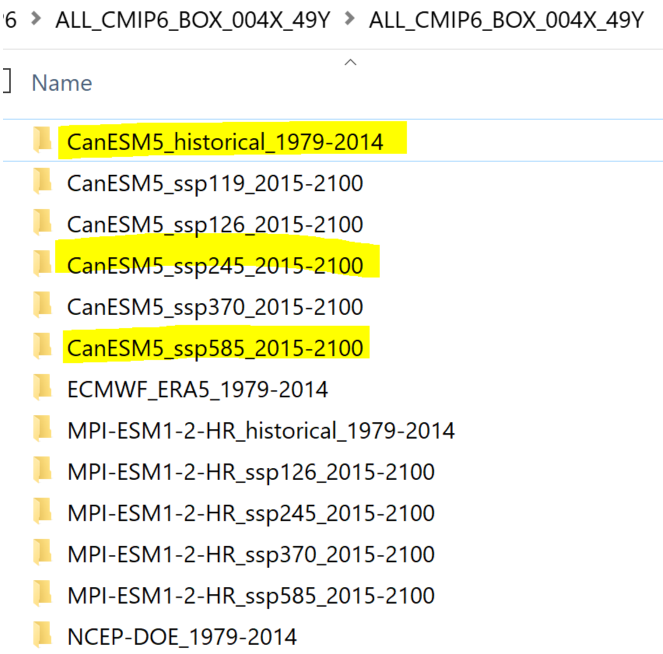

Figure 3.3: Downloaded CMIP6 data

The output files of the scenario generation are the historical model as well as the SSP4.5 and SSP8.5 models.

3) Bias Correction

As already indicated in the introduction, for the historical model an additional step is performed in SDSM. In fact, the historical model/scenario is compared with the raw observation data. This verifies the appropriateness of the selected predictors used to create the models. To use the compare function in SDSM, foremost summary files of the observation data and the historical models are created. Then the two data sets can be displayed as curves in line charts. If the two curves match, the predictors are appropriate to predict the future climate and it is proceeded with the creation of the SSP4.5 and SSP 8.5 models. The results of the historical model's comparison are shown as line charts in the Appendix D. The result shows deviations in the precipitation models in some places, which makes a correction necessary. The temperature models, on the other hand, match and therefore the historical model and the applied predictors are appropriate and the data is used without correction.

The following Figure 3.5 is an example based on the BER climate station. The three historical models are shown. The two temperature models match, therefore the observed data and the created historical model match. For precipitation there are deviations in certain months, therefore a bias correction is necessary.

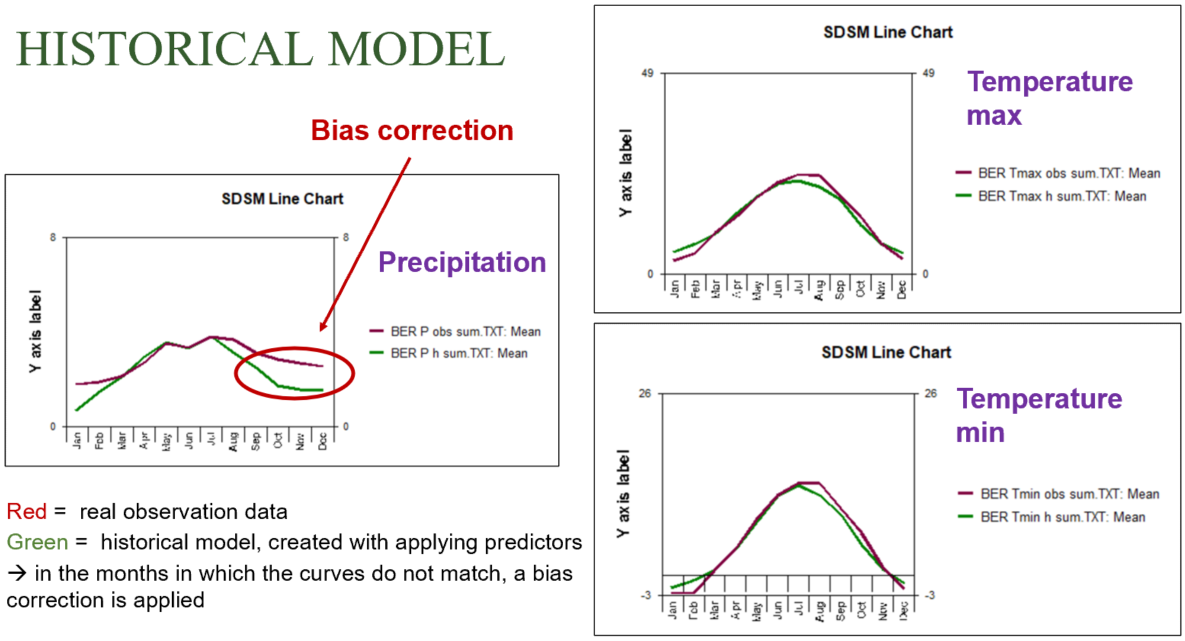

Figure 3.4: Validation of Historical Model

In the months in which the curve of the precipitation observation data deviates from the curve of the historical model, a bias correction is carried out as follows: The text files of the two data sets are opened to calculate the difference. This difference is then added to or subtracted from the monthly data of the models. If the observation data shows more rainfall, and therefore this curve is above the curve of the historical model, the difference is added. If the observation data show less rainfall or the curve of the observation data is below that of the historical model, the difference is subtracted. Table 3.4 gives an overview over the correction made. A detailed description on the bias correction is shown in Appendix E.

Table 3.4: Bias correction for Precipitation

Station	**Months affected**	**Difference (in mm)**	**Add or subtract in data set of Model SSP 4.5 / SSP 8.5**
BER	October	1.1	add
	November	1.1	add
	December	1.0	add
LUG	April	1.4	add
	May	2.0	add
	June	2.8	add
	July	1.8	add
	August	1.8	add
	September	1.6	add
	October	1.3	add
	November	2.9	add
SAE	June	1.7	add
	July	2.6	add
SBE	August	2.2	add
	October	-1.8	subtract
	November	-2.1	subtract
	December	-2.4	subtract

3.6 Reliability Assessment Process

To ensure that the regional climate model for Switzerland is reliable and consistent based on the SSP scenarios, a reliability assessment is carried out in SPSS Statistics 25 and Microsoft Excel 365. The reliability tests are based on the generated RCMs SSP4.5 and SSP8.5 and conducted for the years 2015–2100. As preparation, the total monthly rainfall and average monthly temperature data is prepared in Excel. The monthly observation data is used, because previous studies have shown that the daily data are too raw and not reliable. It is recommended to narrow it down and use the accumulated monthly data.

An overview over the reliability tests is given in Figure 3.6. Since there is benchmarking data from 2015 – 2021 available, the analysis can be conducted for this time period. As stated in Chapter 2, the analyses carried out are Linear Regression, Cronbach's Alpha and Probability Density Function (PDF). The first both mentioned tests will be run in SPSS Statistics 25. The PDF test will be conducted in Microsoft Excel 365.

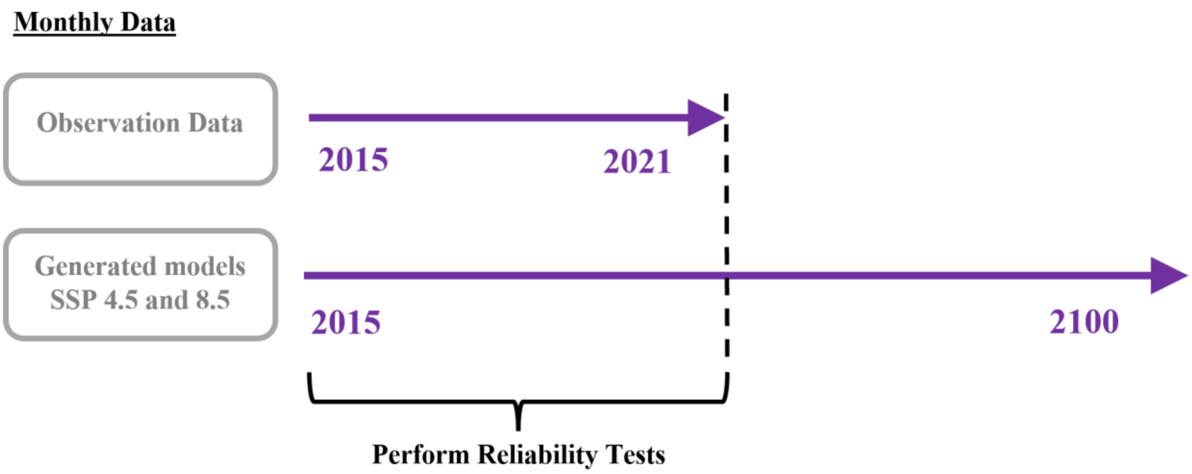

Figure 3.5: Reliability Assessment

In summary, the reliability tests can be applied to evaluate the SSP4.5 or SSP8.5 scenario, which is most likely to occur based on observation data (2015-2021). The SSP model that performs better in the reliability tests, is recommended in this study.

3.7 Spatial Analysis (QGIS)

In order to generate the rainfall map for Switzerland, the rainfall data is prepared as the average of annual rainfall from 1991-2021 (30 years period). After the rainfall data preparation, the study area layer is created by using “toggle” together with the “add polygon feature” tool, followed by interpolation, by choosing the average annual rainfall data using IDW technique. The interpolated output undergoes masking and clipping by shapefile of boundary of Switzerland and editing to give colour by referring to the rainfall values. Lastly, the rainfall map generation is created by using the function “new print layout. The completed average annual rainfall map for the 30 years period is generated with north direction indicator, legends and scalebar.

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the results are presented and discussed. First, the generated historical models are validated. Second, the generated RCMs for the Scenarios SSP4.5 and SSP8.5 are presented and discussed. Following the output of the reliability assessment is interpreted. Finally, the more suitable scenario is recommended and rainfall maps of the selected scenario analysed.

4.1 Validation of Historical Model

As already mentioned in the Downscaling Methodology part, the Historical Model was compared with the raw observation data. This was done in SDSM by generating summaries of files of the data and then plotting both data series on a line chart. The both curves should match to show that the selected predictors are appropriate. The aim is to check the appropriateness of the predictors to build the Regional Climate Models with solid data.

In general, the result show deviations in the precipitation models in some places, which were corrected by a bias correction. The temperature models, on the other hand, match and therefore the historical model and the applied predictors can be considered appropriate and the data can be used without correction. The results of the historical model's comparison are presented and discussed below.

4.1.1 Precipitation

The precipitation diagrams of the four stations are shown in Figure 4.1, Figure 4.2, Figure 4.3, and Figure 4.4, respectively. The red curve represents the observed data, while the green curve represents the created historical model. There are different possible reasons for a mismatch of the two curves, which are following evaluated.

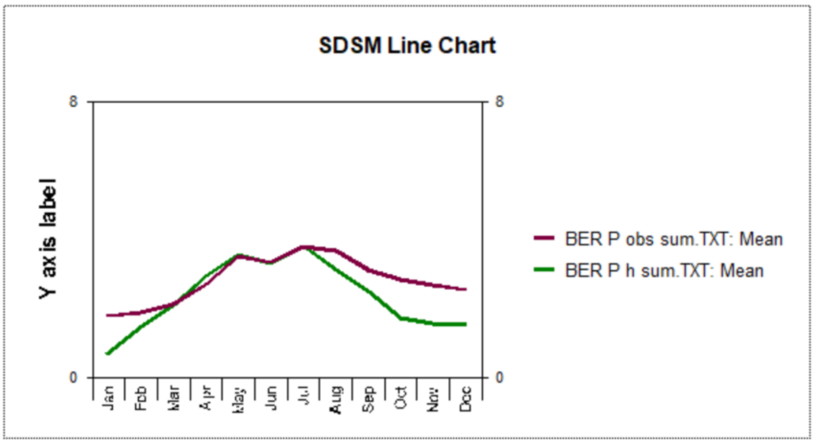

Figure 4.1: Historical Model BER Precipitation

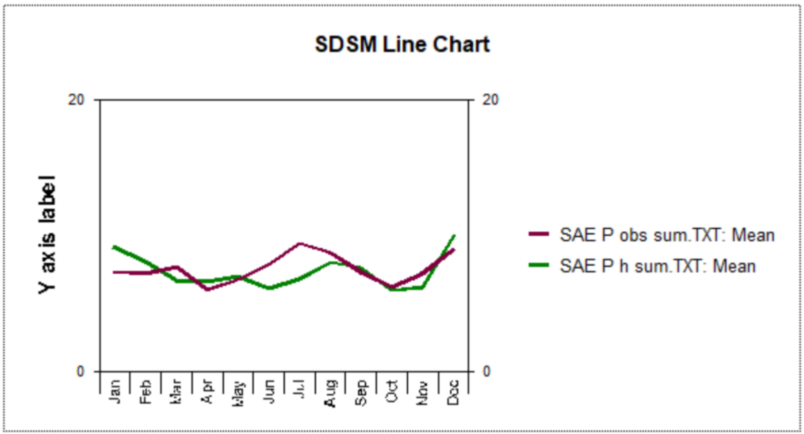

Figure 4.2: Historical Model SAE Precipitation

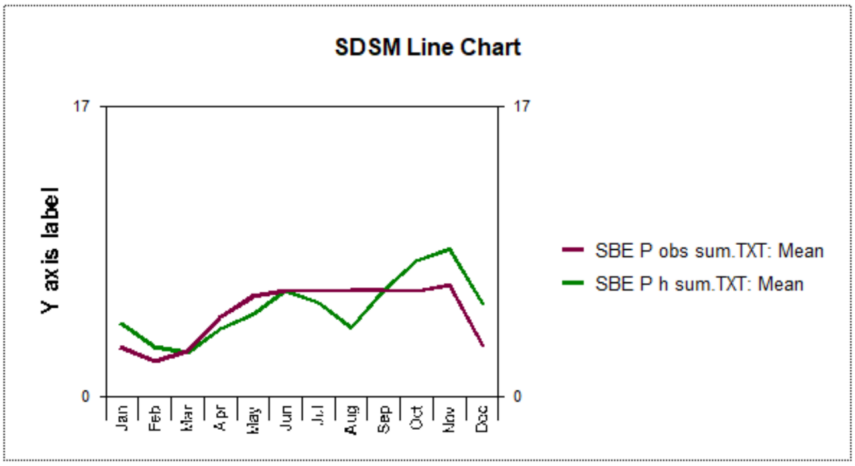

Figure 4.3: Historical Model SBE Precipitation

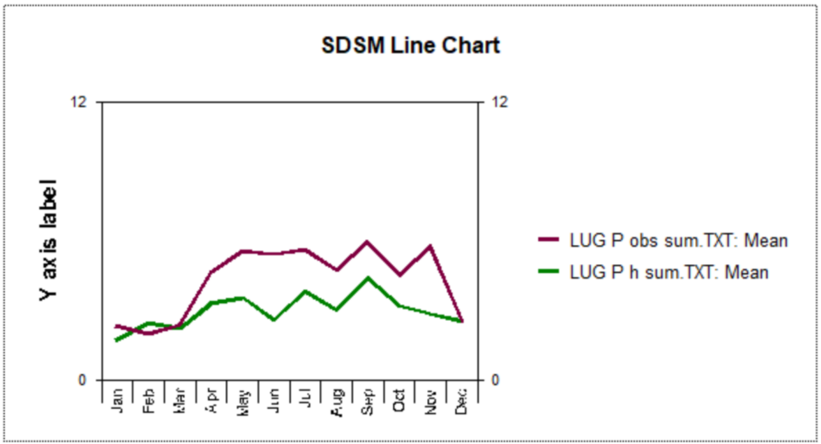

Figure 4.4: Historical Model LUG Precipitation

First, the predictors used to create the model may not be appropriate for the specific region or time period, leading to a poor fit between the model and the observations. The specific region was determined precisely because the cell box containing all 4 climate stations in Switzerland was selected. On the other hand, the predictors are already 10 years old (1850-2014), which might no longer be considered up-to-date due to the rapid increase in greenhouse gases in the atmosphere and therefore a fast change in climate patterns. Second, it is possible that the predictors used in the model do not fully capture the complex processes that determine precipitation in Switzerland, resulting in a discrepancy between the model and the raw observations. Pichelli et al. (2021), who provide insights into the spatial and temporal patterns of precipitation across different models in Switzerland, state that the prediction of precipitation is challenging as the wind strength in the alpine region varies from day to day, changes rapidly and snowfall must also be taken into account in the analysis. Further, Switzerland is also known for its microclimates, which can cause significant variations in temperature and precipitation over short distances. For example, Ticino in the south of the country has a Mediterranean climate with warm temperatures and frequent sunshine, while Engadin in the east has a cold, dry climate with little precipitation (WorldData, 2023). There may be errors or biases in the raw data used to create the model or in the observations used to validate the model. This can be negated because the raw data was checked for inconsistencies and incompleteness at the beginning and the calibration in SDSM was also carried out twice to avoid errors. The statistical downscaling model may have inherent limitations or assumptions that do not fully capture the variability of precipitation in the region or time period of interest. The time period could be a cause, since - as already mentioned - the predictors only extend into 2014. The raw data were collected as recently as possible and cover the time span from 1991 - 2021. Last, there may be natural variability in precipitation that is not captured by the model or the observations, leading to differences between the two curves. Models are always based on assumption and Ban et. al (2021), who present an evaluation of precipitation in a multi-model ensemble of regional climate simulations over Switzerland, state that there are still many deficiencies in these modelling system that need to be addressed in the future.

4.1.2 Temperature maximum

The charts Figure 4.5, Figure 4.6, Figure 4.7 and Figure 4.8, respectively, for Temperature maximum show a high degree of match. From this can be concluded that the selected predictors are appropriate. At the SAE station, a deviation can be seen in the months July, August, September, which is because the station is located on an exposed mountain (Mountain Säntis) and the temperature is very changeable during this season (transition summer - autumn). Additional, high temperatures have been measured more frequently in recent years what is not included in the predictors yet.

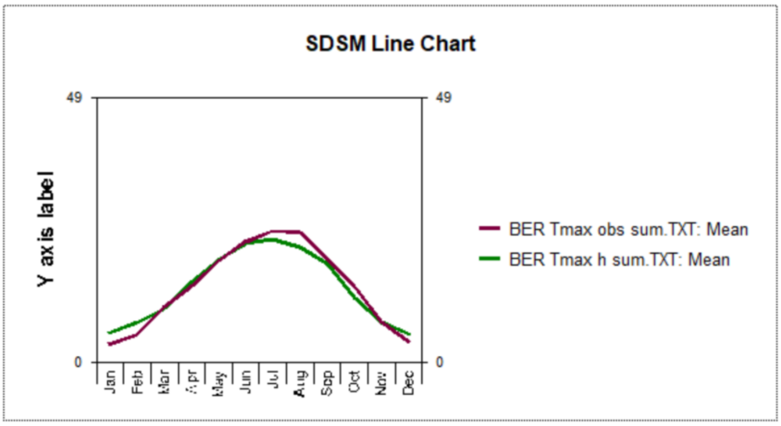

Figure 4.5: Historical Model BER Temperature maximum

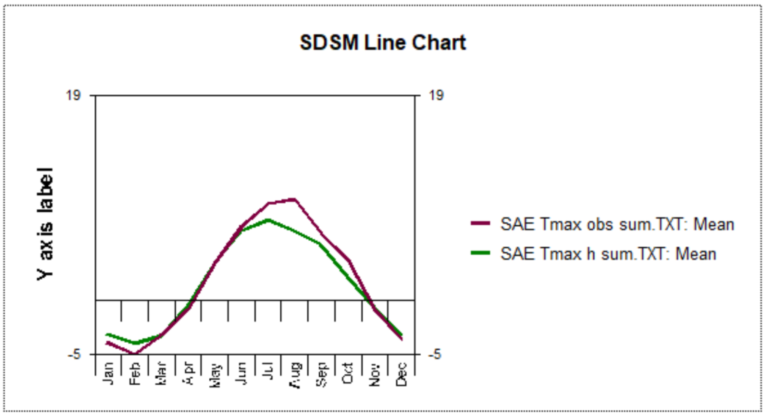

Figure 4.6: Historical Model SAE Temperature maximum

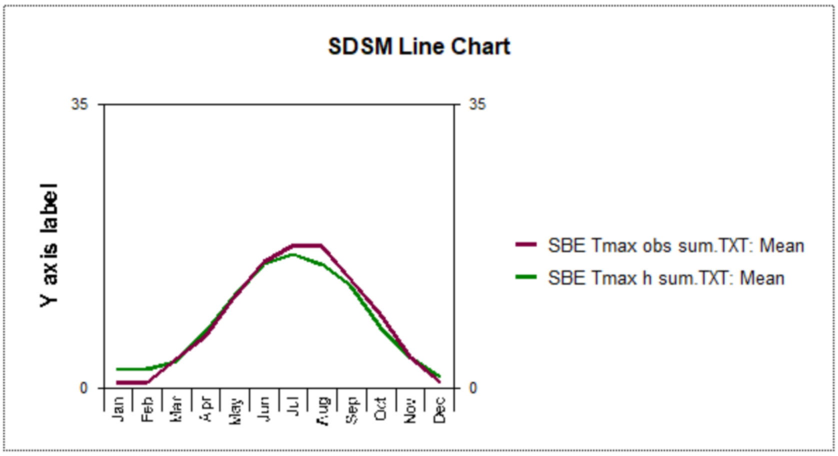

Figure 4.7: Historical Model SBE Temperature maximum

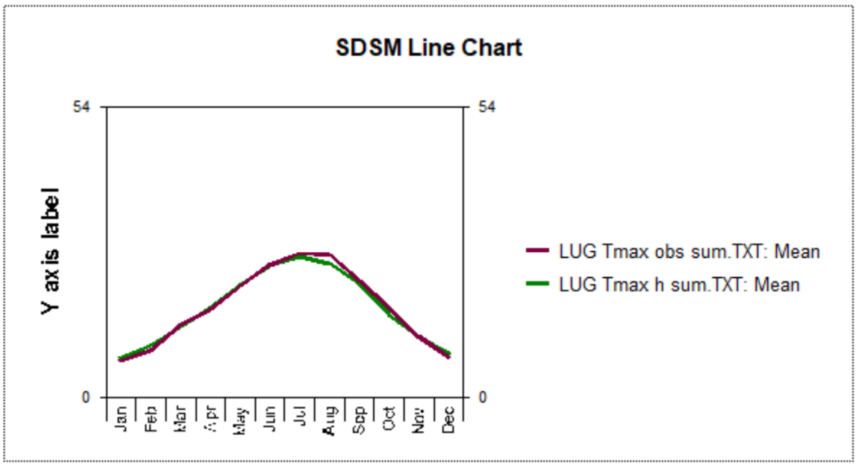

Figure 4.8: Historical Model LUG Temperature maximum

4.1.3 Temperature minimum

For the minimum Temperatures, the curves of Figure 4.9, Figure 4.10, Figure 4.11 and Figure 4.12 also show a high degree of conformity, which indicates an appropriate selection of predictors. It can also be seen (as with temperature max) in autumn, which can be explained by the varying temperatures in the transition from summer to autumn. In addition, the observed data show colder values in February, which can be explained by the fact that there have always been colder extreme values in recent years, which is probably not yet reflected in the predictors.

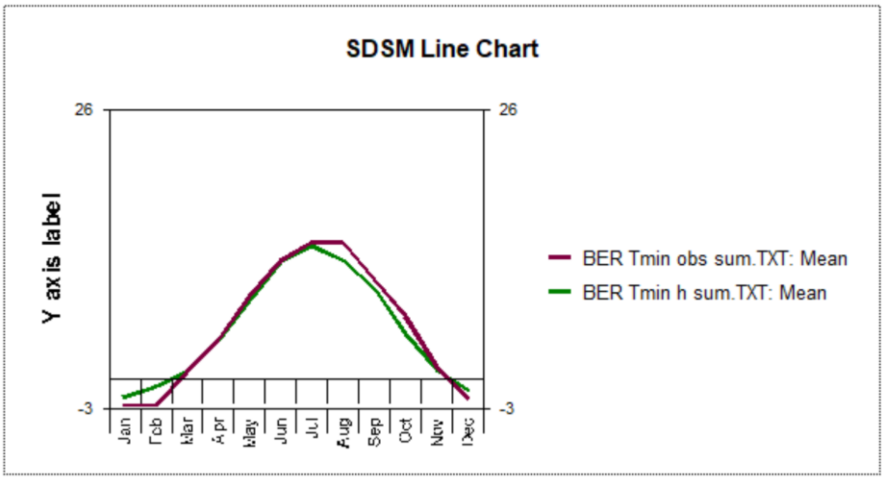

Figure 4.9: Historical Model BER Temperature minimum

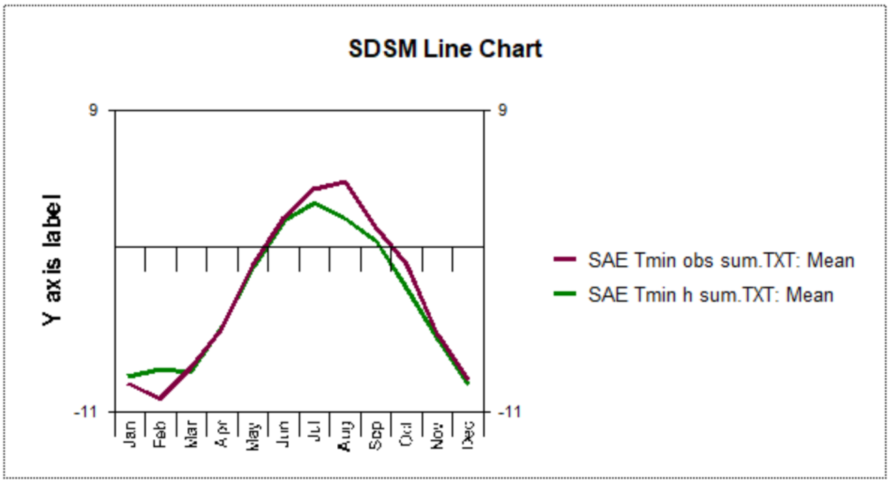

Figure 4.10: Historical Model SAE Temperature minimum

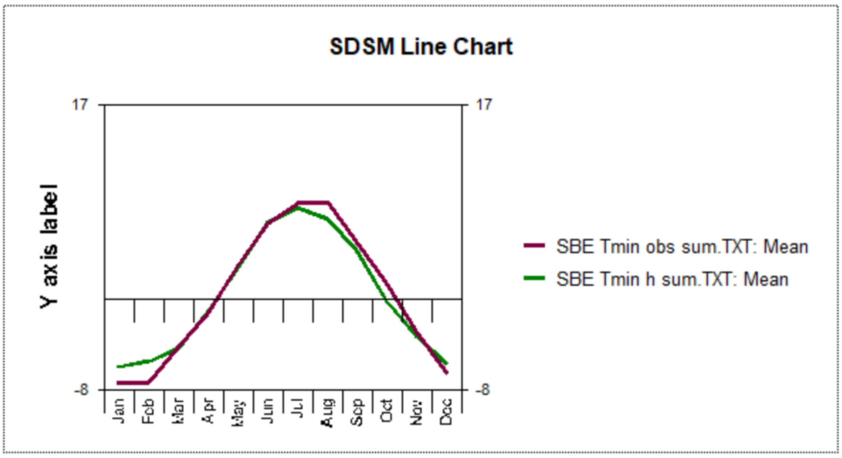

Figure 4.11: Historical Model SBE Temperature minimum

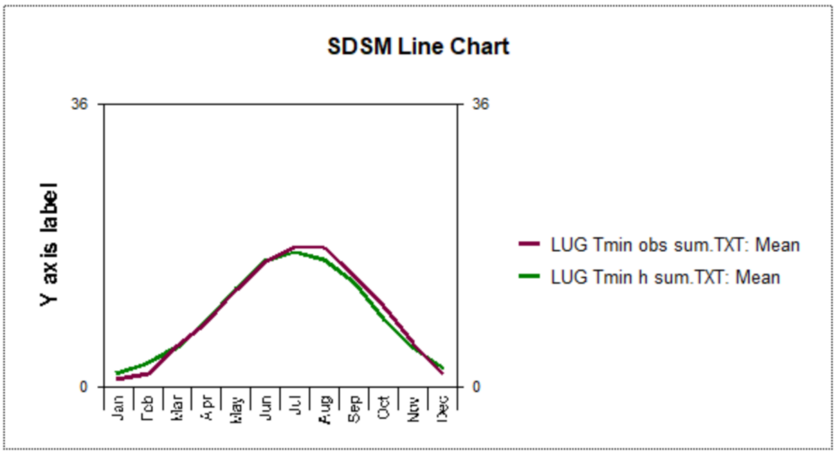

Figure 4.12: Historical Model LUG Temperature minimum

4.2 RCMs SSP4.5 and SSP8.5

The Regional Climate Models for the scenarios SSP4.5 and SSP8.5 were developed in SDSM. As a brief reminder, SSP4.5 is the Middle of the Road scenario. This scenario assumes a world with moderate economic growth and a gradual shift towards cleaner energy sources, but with continued reliance on fossil fuels. SSP8.5 is also referred as the Fossil-Fueled Development scenario. This scenario assumes a world with high economic growth, driven by the expansion of fossil fuel use, with limited concern for environmental protection or social equity.

The created RCMs are presented below. First, the precipitation models are discussed, followed by the temperature models. In the models, the study period from 2020 to 2100 is divided into intervals of 20 years.

Interval (year dates)	**Colour**
2020 to 2040	**Blue**
2040 to 2060	**Orange**
2060 to 2080	**Grey**
2080 to 2100	**Yellow**

The four intervals are shown as curves in different colours in the charts below. The x-axis of the charts shows the month of the year and the y-axis the amount of Precipitation (in mm) or Degree Celsius °C, respectively. The values are average monthly values. The models for the two pathways are shown side by side to enable a comparison. The two models are presented one after the other, first SSP4.5 and then SSP8.5. In addition, a description of the current precipitation and temperatures is given at the beginning so that the models can be compared not only with each other but also with the current measured values.

4.2.1 Precipitation

Climate Station Bern (BER)

Current precipitation at station: Bern receives moderate rainfall throughout the year. The wettest months are typically from May to August, with an average of around 100-120 mm of rainfall per month. In contrast, the driest months are usually December to February, with an average of around 50-60 mm of rainfall per month. Snowfall is also common in Bern during the winter months, with an average of around 50-60 cm of snowfall per year. The heaviest snowfalls usually occur in January and February.

The models in Figure 4.13 show that the wettest months in Bern are still May to August. However, the amount of rain increases significantly, especially in the summer months of June and July. SSP4.5 shows precipitation values up to 150 mm in the interval 2080-2100, while in SSP8.5 it shows even 180 mm. At the moment the location recorded 100-120mm of rainfall in their wet months. And the driest months remain December to February. However, the amount of rainfall decreases. While it is 50-60 mm now, in the future it will only be between 30-40 mm in February, for example. It is also evident that the first interval (2020-2040) behaves quite differently from the other three intervals (particularly evident in SSP4.5). This shows that the extreme changes in precipitation are "only" to be expected from 2040 onwards. Basically, it can be stated that precipitation values will be more extreme in the future, with more precipitation in wet months and less in dry months.

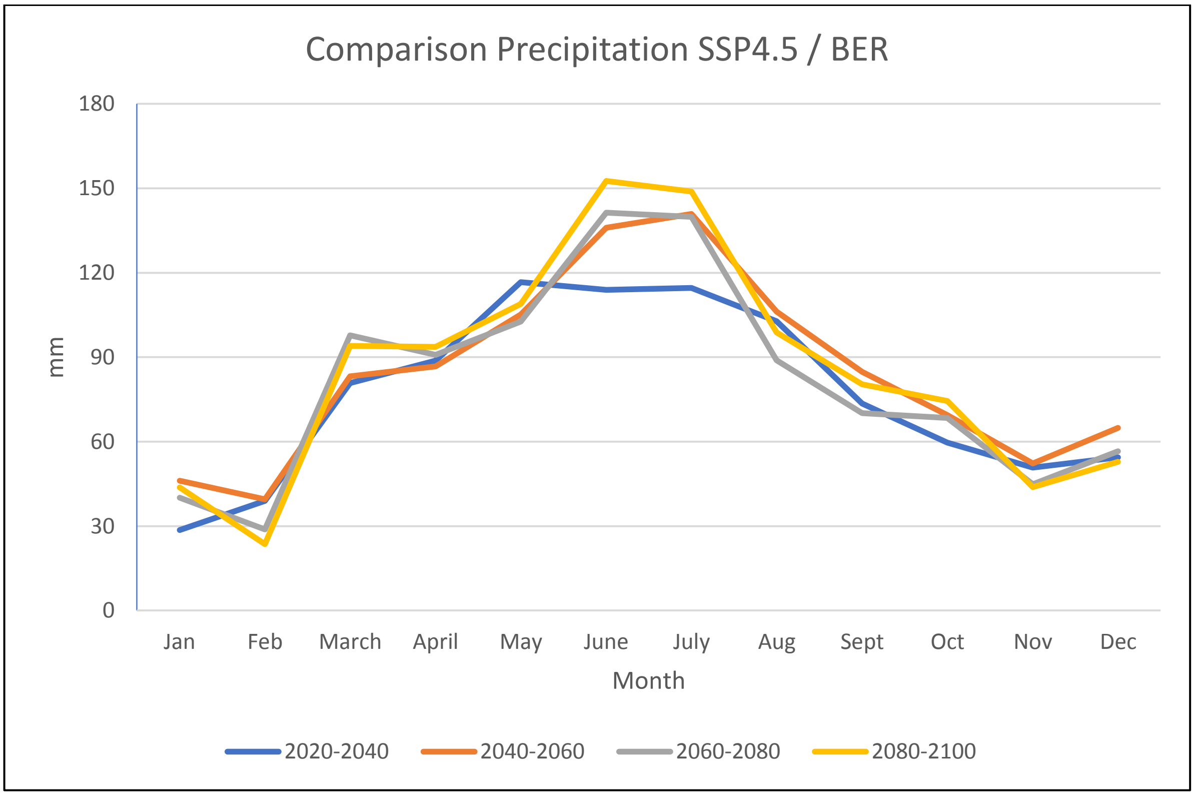

Figure 4.13: RCM Precipitation SSP4.5 – BER

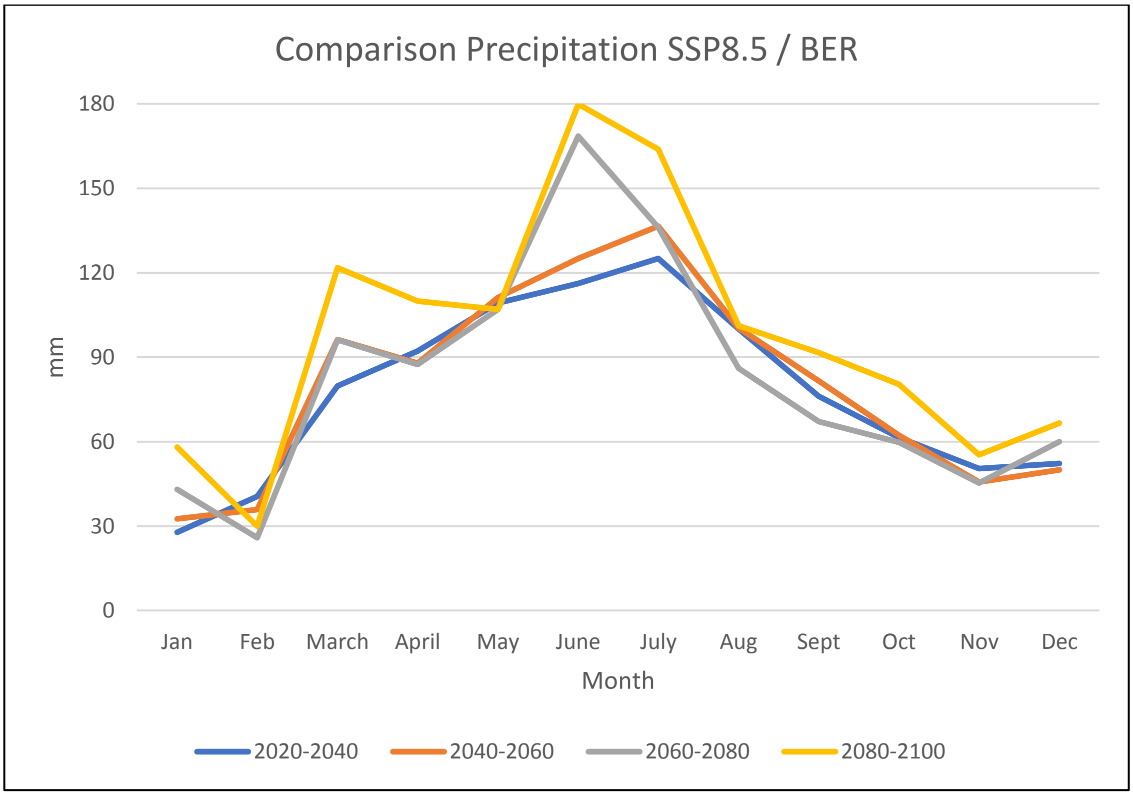

Figure 4.14: RCM Precipitation SSP8.5 – BER

Climate Station Säntis (SAE)

Current precipitation at station: Säntis receives a significant amount of rainfall and snowfall throughout the year, due to its high altitude and location in the mountains. The wettest months are typically from May to September, with an average of around 200-300 mm of rainfall per month. The winter months of December to February are also relatively wet, with an average of around 100-150 mm of precipitation per month. Snowfall is common in Säntis throughout the year, with an average of around 10-12 meters of snowfall per year. The heaviest snowfalls usually occur in the winter months of December to February.

The climate models in Figure 4.14 show similar patterns for the Säntis station. The four intervals behave similarly. SSP4.5 shows that precipitation decreases from the first interval (2020-2040) to the second interval (2040-2060). However, it then increases again in the third (2060-2080) and fourth interval (2080-2100), but no longer reaches the amount of the first interval. The SSP8.5 shows the lowest values for the winter months in the first interval, but higher values are then displayed in the summer months compared to the other 3 intervals. Overall, it can be noted that for this station the precipitation amounts follow clear trends in the future and there is not a big difference between the two scenarios. The comparison with the current situation is exciting. Currently, May to September are the wettest months, which will change. The two climate models produced show that November to January will record the highest precipitation amounts in future. The months of December to February are also quite wet, but currently record only 100-150 mm, while the models show that precipitation will be up to 370 mm in January. However, the values in December and February will be around 250-300 mm. May to September currently records 200-300 mm of precipitation per month, in the future this will decrease a bit and range between 200-250 mm.

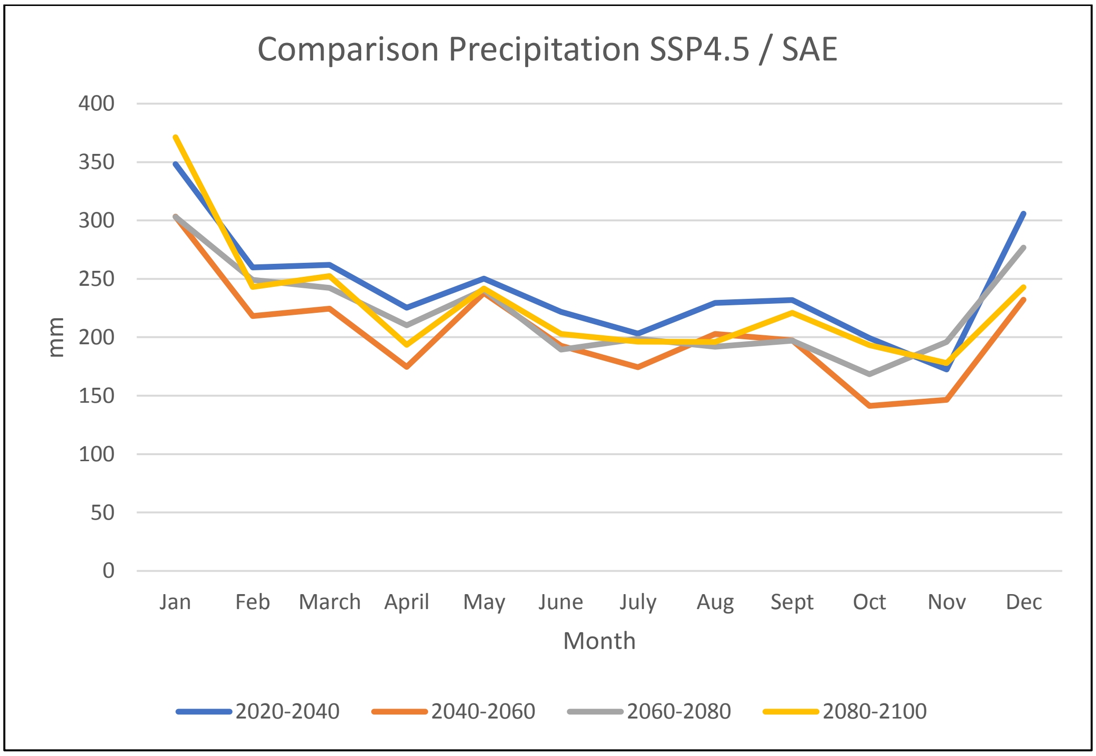

Figure 4.15: RCM Precipitation SSP4.5 – SAE

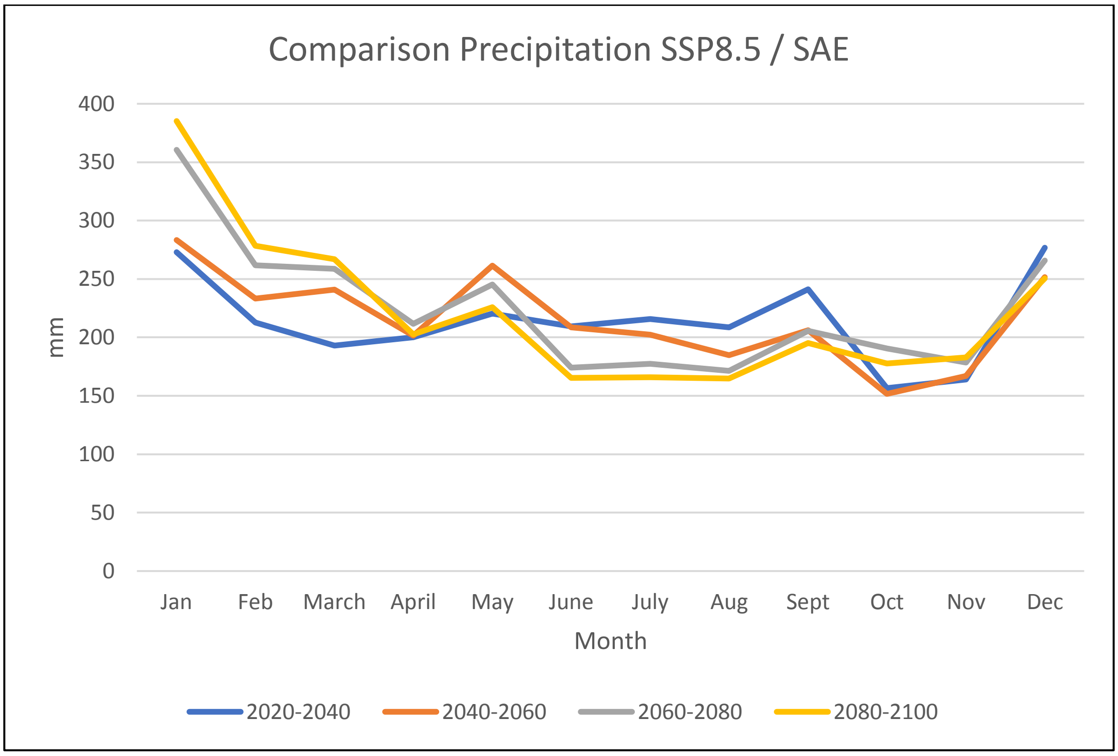

Figure 4.16: RCM Precipitation SSP8.5 – SAE

Climate Station S. Bernardino (SBE)

Current precipitation at station: S. Bernardino receives a moderate amount of rainfall and snowfall throughout the year. The wettest months are typically from May to August, with an average of around 100-150 mm of rainfall per month. The winter months of December to February are the driest, with an average of around 30-40 mm of precipitation per month. Snowfall is common in S. Bernardino during the winter months, with an average of around 4-5 meters of snowfall per year. The heaviest snowfalls usually occur in January and February.

Both climate models in Figure 4.15 show a similar pattern over the years and it is evident that precipitation will increase over the years until 2100. The blue curve, which represents the interval 2020-2040, shows the lowest values across all months. In both models, the summer months of June and July show that the amount of rainfall will increase significantly (up to 300 mm in SSP4.5 and 370 mm in SSP8.5). But the months of October to December also record high rainfall (the values are in the same range as in the months of June and July), while the months February to April record little rainfall (only around 80-130 mm). Comparing the two models, the SSP8.5 model shows slightly more extreme values, which means that more precipitation is recorded. Currently, the months of May to August are the wettest with around 100-150 mm. As it can be seen from the model, this will focus on the months of June and July in the future. On the other hand, the winter months of December to February are the driest with precipitation around 30-40 mm per month. The two climate models show that the dry months will shift to February to April (especially clearly visible in SSP4.5) and that precipitation will also increase in these months (in SSP4.5 around 90-130 mm and in SSP8.5 around 90-170 mm).

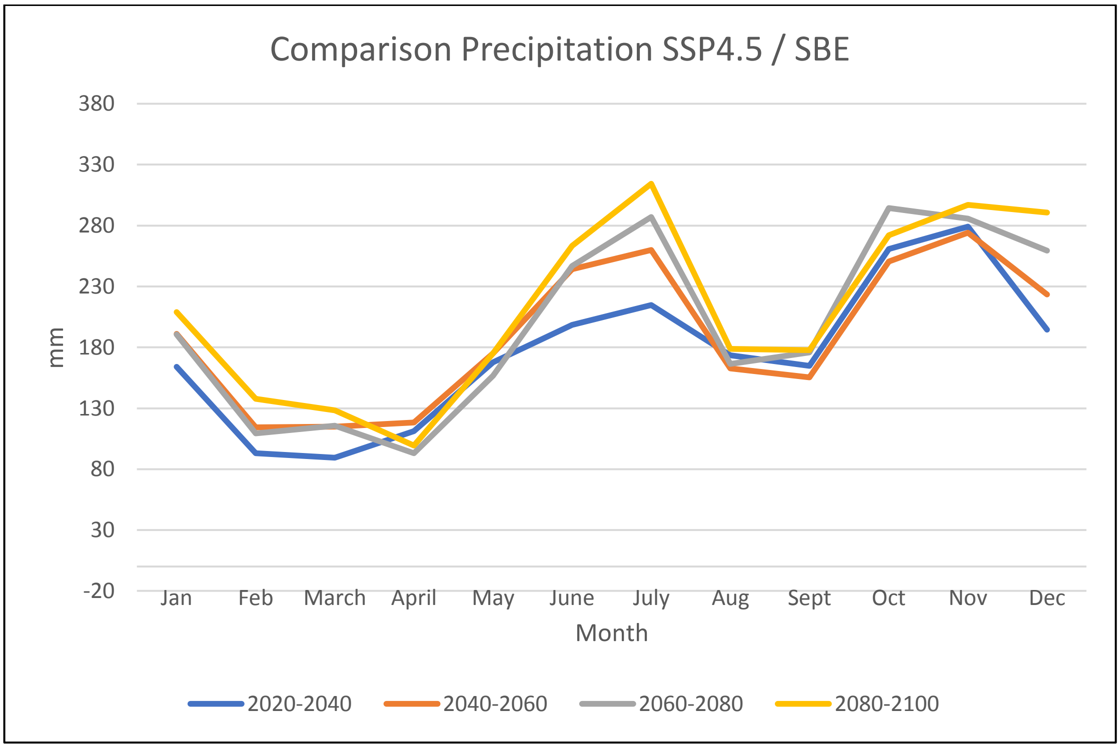

Figure 4.17: RCM Precipitation SSP4.5 – SBE

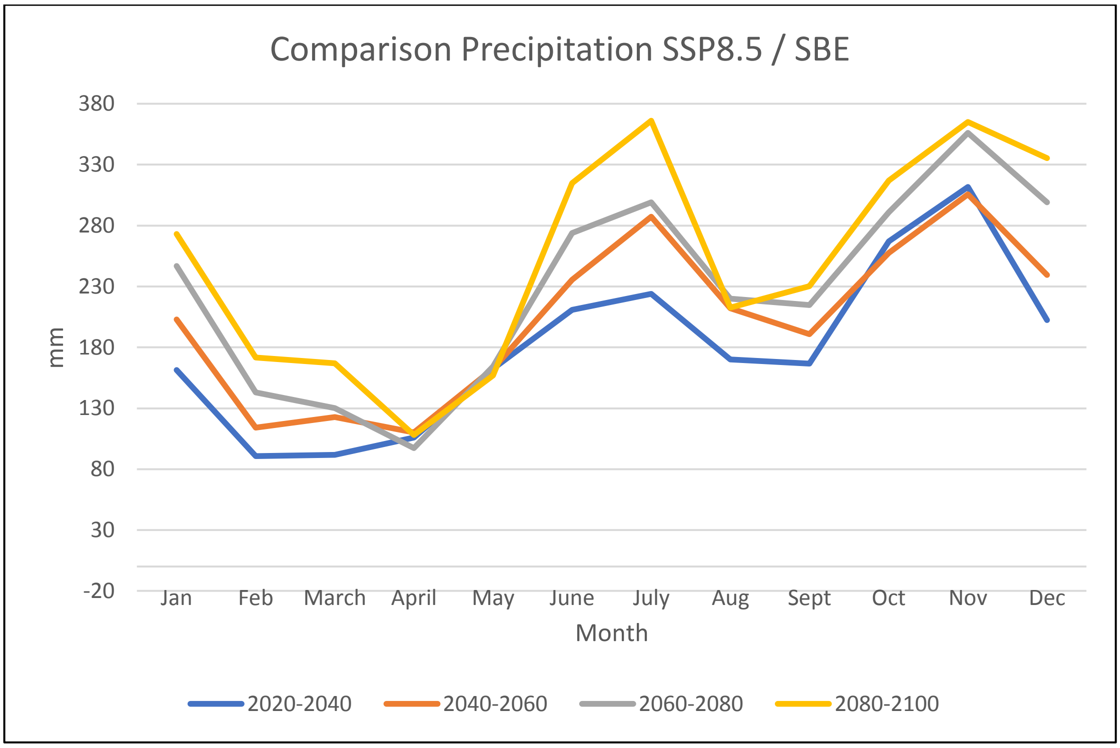

Figure 4.18: RCM Precipitation SSP8.5 – SBE

Climate Station Lugano (LUG)

Current precipitation at station: Lugano is known for being one of the driest and sunniest places in Switzerland. The city receives the least amount of rainfall in Switzerland, with an average of around 1,200 mm of rainfall per year, which is less than half of the national average. The driest months in Lugano are typically from October to March, with only around 40-60 mm of rainfall per month, while the wettest months are from May to September, with an average of around 100-150 mm of rainfall per month. Thunderstorms are also common in Lugano during the summer months. The city rarely experiences snow, with only a few centimetres falling each year.

The two climate models in Figure 4.16 show a similar pattern for Lugano. The first interval (2020-2040) shows lower values for all months, indicating that precipitation will increase in the following 20-year intervals. It can be noticed, when taking a closer look, that in both models the first two intervals (blue and orange curve) behave differently, while the last two intervals give a similar picture. The interval 2020-2040 in SSP4.5 shows the highest precipitation in the summer months and less precipitation during the winter. In SSP8.5, on the other hand, the same interval shows a uniform precipitation amount with precipitation between 60 to 120 mm. The last two intervals (2060-2080 and 2080-2100) show precipitation peaks in June and October. The values in the SSP4.5 move up to 180 mm, while the SSP8.5 displays up to 230 mm. Lugano currently records the driest months from October to March with around 40-60 mm rainfall per month. Both climate models predict that October will be a wet month in the future, but after that the amount of precipitation will decrease as usual. The wettest months are currently from May to September with an average of around 100-150 mm per month. This wet period will be maintained in the future and in addition October will be added as a wet month (as mentioned earlier). In addition, the months will be recording more precipitation, average between 120-160 mm.

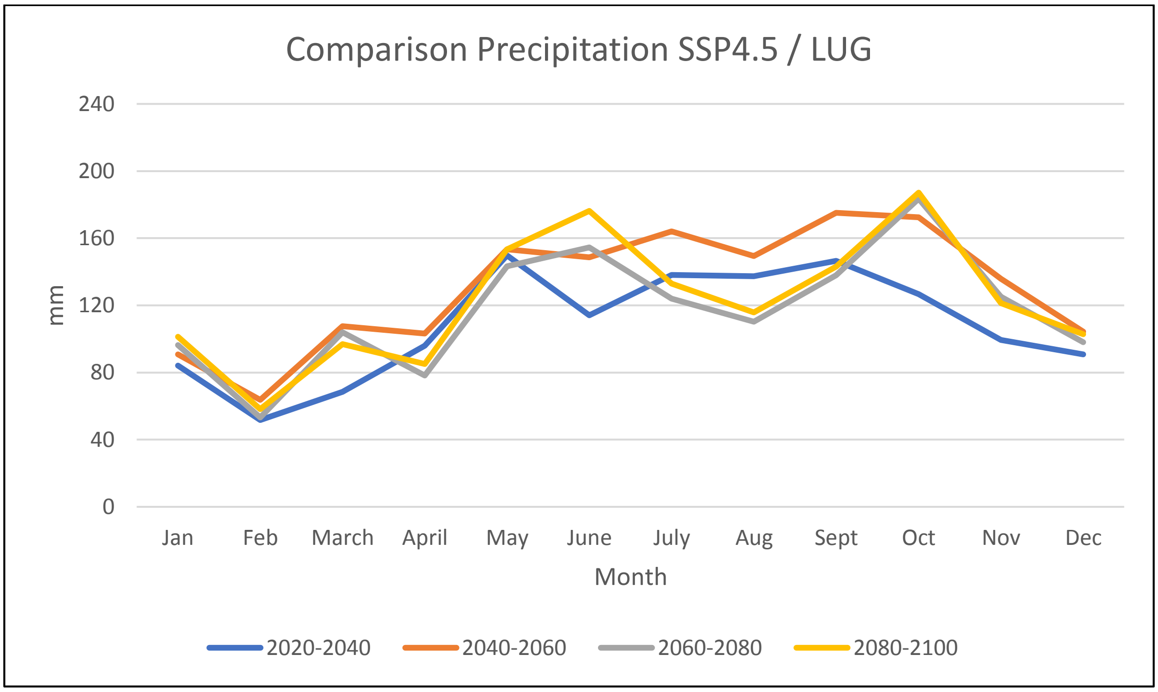

Figure 4.19: RCM Precipitation SSP4.5 – LUG

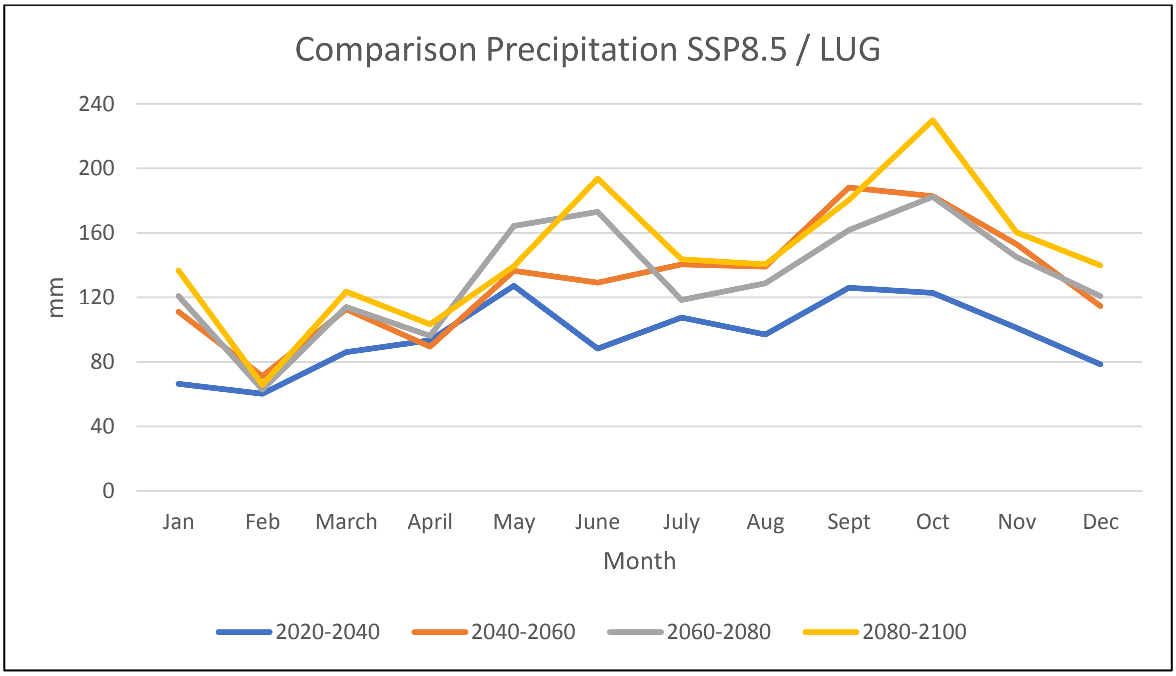

Figure 4.20: RCM Precipitation SSP8.5 – LUG

4.2.2 Temperature maximum

Climate Station Bern (BER)

Current temperature at station: The temperature maximum in Bern varies throughout the year, with the warmest months typically being July and August. During these months, the average high temperature is around 25°C, but temperatures can occasionally reach as high as 30°C or higher. In the cooler months of December to February, the average high temperature is around 2-3°C. However, temperatures can drop below freezing, particularly at night.

Both climate models in Figure 4.17 show a similar pattern over the course of the maximum temperature in Bern. SSP8.5 shows more extreme values, which means that the intervals show higher temperatures than in SSP4.5. Both models show the next interval (2020-2040, blue curve) in the same temperature range from around 7°C in winter to 26°C in summer. The following intervals then show a stronger increase in temperatures in SSP8.5 than SPP4.5, i.e. more extreme temperature values. Currently, the summer months of July and August record the highest temperatures in Bern. According to the models, this will not change. The cold months will also remain December to February. Currently, the maximum temperatures during these months are around 2-3°C, but the temperature will rise in the next few years, as the climate models show. In the SPP4.5 scenario, temperatures around 7-8°C are expected and in the SSP8.5 temperatures between 6°C and 12°C (depending on the interval).

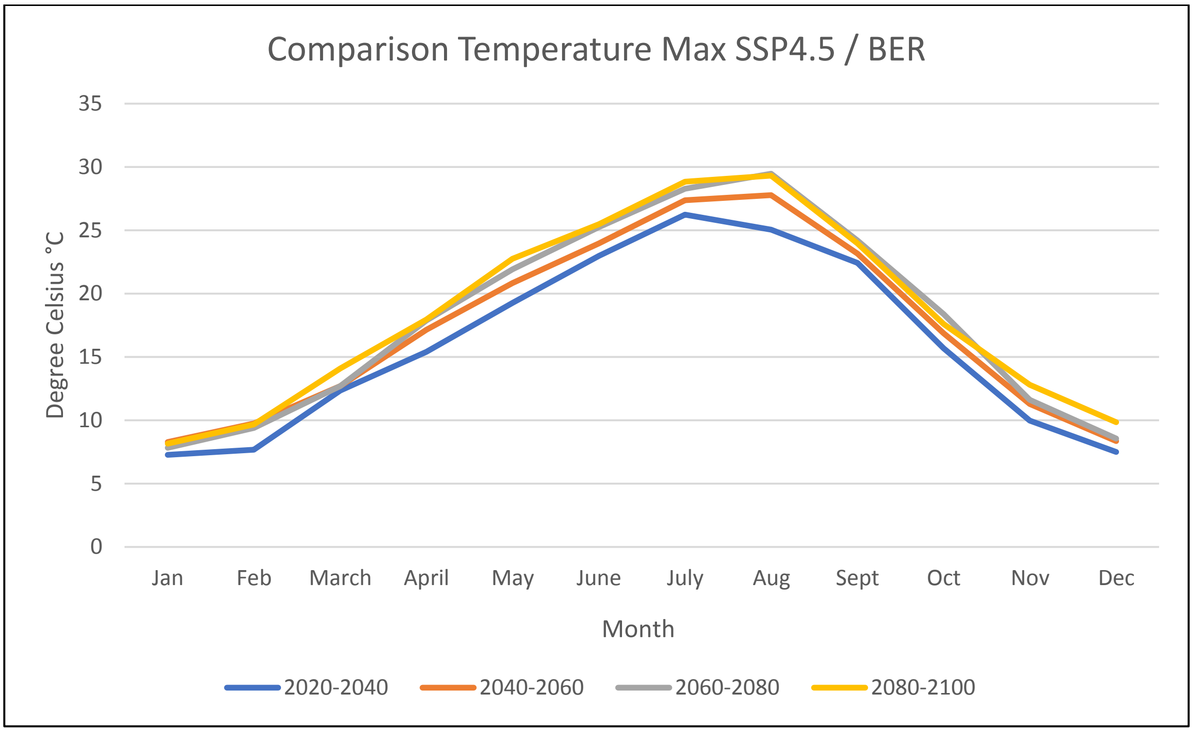

Figure 4.21: RCM Temperature maximum SSP4.5 – BER

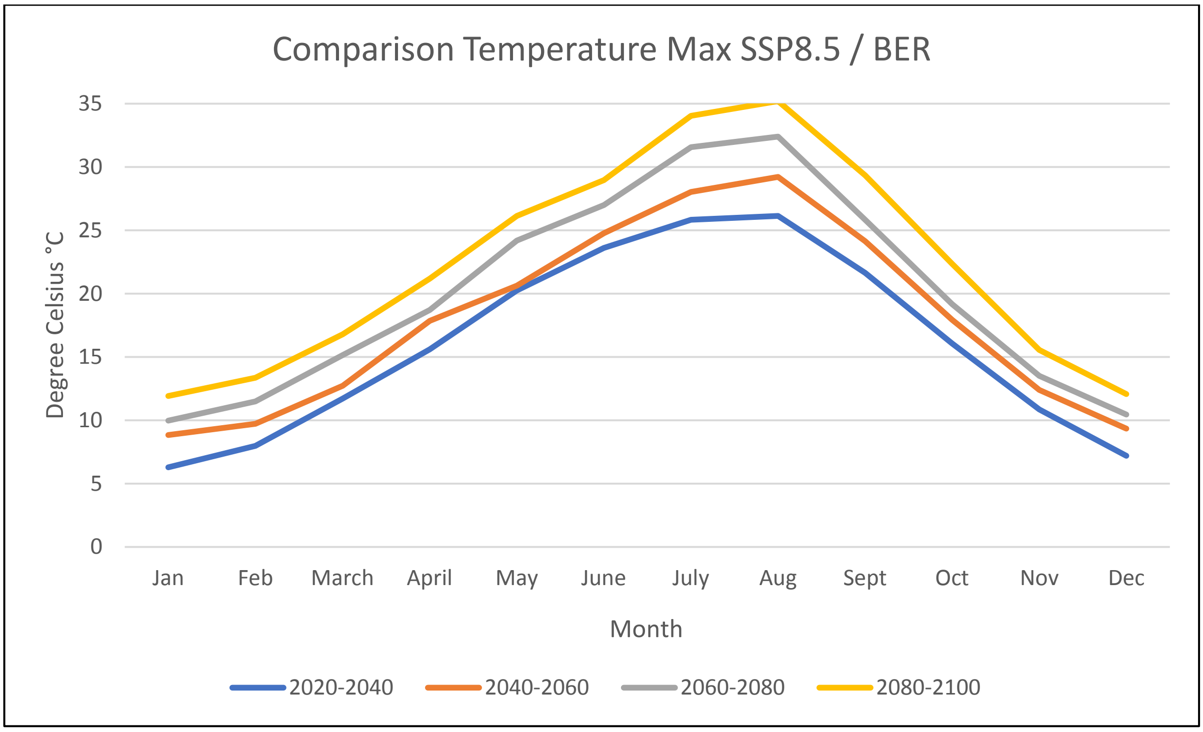

Figure 4.22: RCM Temperature maximum SSP8.5 – BER

Climate Station Säntis (SAE)

Current temperature at station: As a high mountain peak, Säntis experiences cool temperatures throughout the year. The temperature maximum varies depending on the season, with the warmest months being June through August. During this time, the average high temperature is around 10°C, but temperatures can occasionally reach as high as 15°C or higher. In the winter months of December to February, the average high temperature is around -3°C or lower, but temperatures can occasionally rise above freezing during sunny spells.

At the Säntis station, the two climate models also show a similar trend, with warmer temperatures in the summer and cooler temperatures in the winter months (see Figure 4.18). The temperature fluctuations remain the same over the four intervals, but the SSP8.5 shows more extreme temperatures. This means that in SSP8.5 more extreme temperatures are expected in the later intervals. Or in other words: in the future, the temperature maximum will steadily increase. The intervals 2080-2100 (yellow curve) in SSP4.5 show temperature peaks of 15°C in summer, while in SSP8.5 shows 22°C. This is a difference of 7°C. Compared to the temperatures currently measured on the mountain, the temperature curve remains the same. June to August are also currently the warmest months, but a maximum of 10°C average temperatures are measured, compared to 15°C (2020-2040 interval) or higher in the models. The coldest months are also currently December to February with values around -3°C. This is a significant difference between the two models. While the next interval (2020-2040) still shows maximum winter temperatures around 2-3°C, the other intervals show temperatures of 0 in the SSP4.5 scenario and up to 3°C in the SSP8.5 scenario. This is a big increase in maximum temperatures in the winter months. This rise in temperature does not only affect winter, as mentioned briefly earlier, summers will also become hotter and higher temperatures will be measured throughout the year in the future.

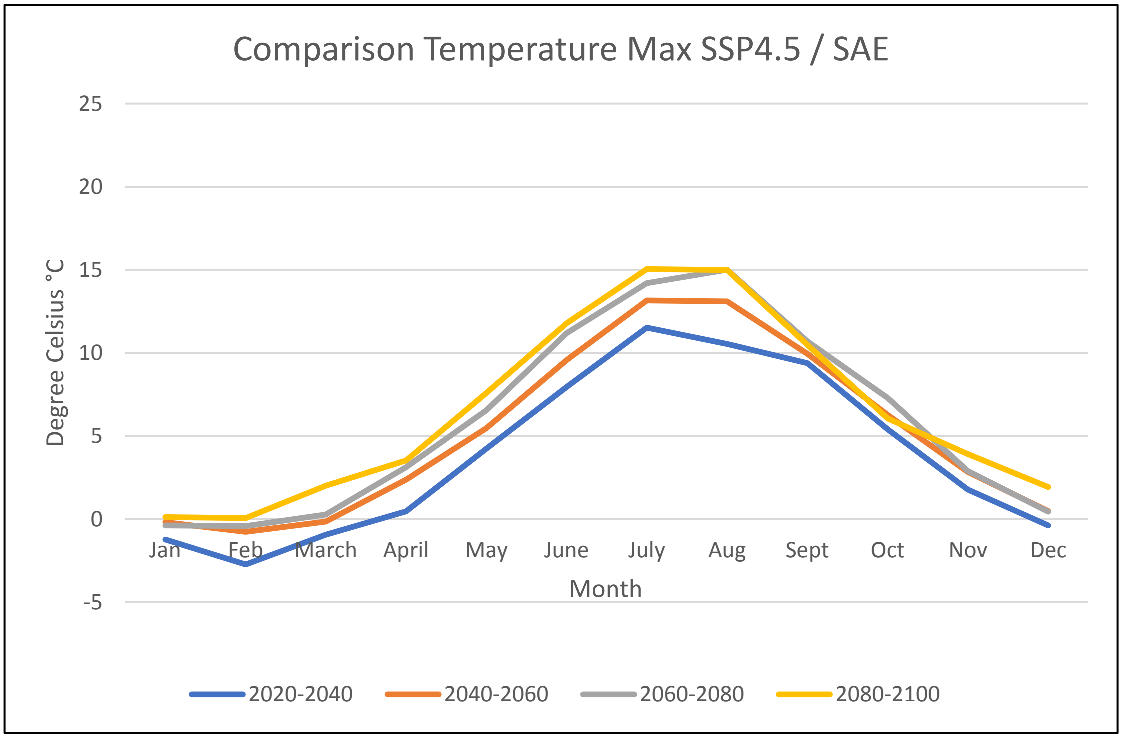

Figure 4.23: RCM Temperature maximum SSP4.5 – SAE

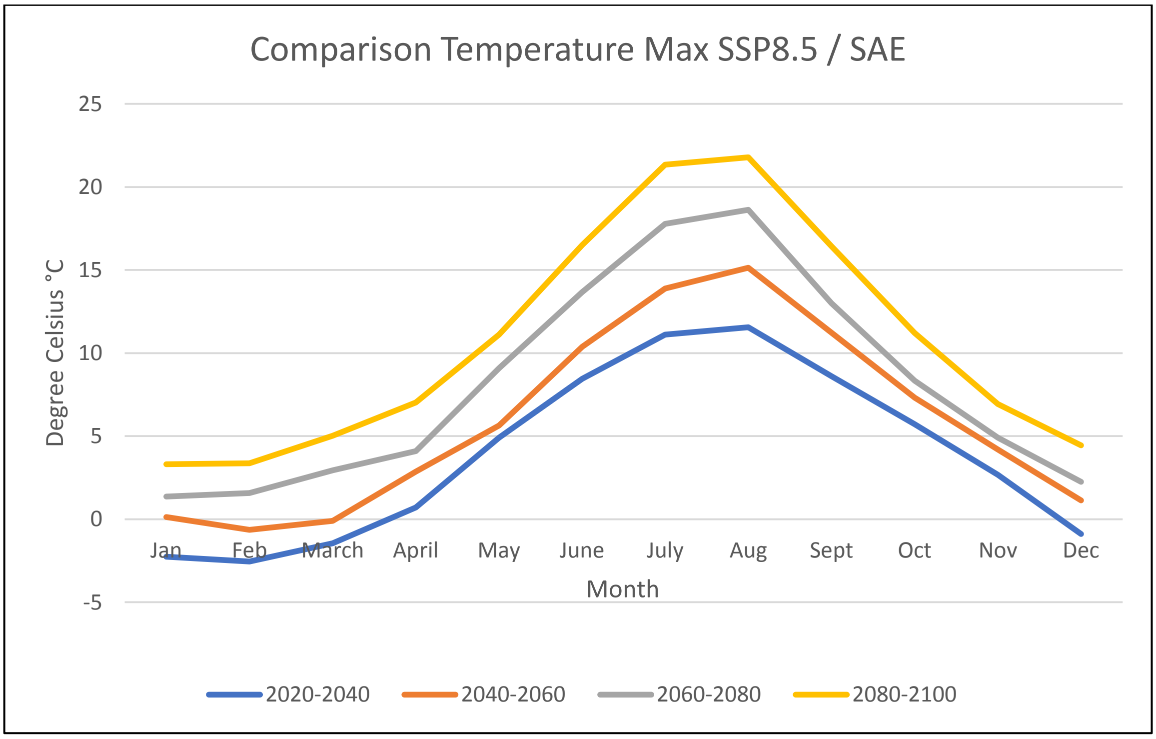

Figure 4.24: RCM Temperature maximum SSP8.5 – SAE

Climate Station S. Bernardino (SBE)

Current temperature at station: As a small village situated in the Alps, S. Bernardino experiences cool temperatures throughout the year, with colder temperatures in the winter months. The temperature maximum varies depending on the season, with the warmest months being June through August. During this time, the average high temperature is around 15°C, but temperatures can occasionally reach as high as 25°C or higher. In the winter months of December to February, the average high temperature is around 2°C or lower, but temperatures can occasionally rise above freezing during sunny spells.

The two curves for S. Bernardino station in Figure 4.19 behave similarly - as they already did with Bern and Säntis. This means that the highest values are measured during the summer months and the lowest during the winter months. As with the previous two stations, the SSP8.5 shows a more extreme rise in maximum temperatures, while the SSP8.5 shows a smaller rise between intervals. The highest temperatures are measured in July and August with between 19-26°C and the lowest in December and January with around 4-6°C. At present, maximum summer temperatures of 15°C are measured, while the models assume 19°C (interval 2020-2040, blue curve) and 22-26°C (interval 2080-2100, yellow curve), resulting in a temperature increase over the next few years.

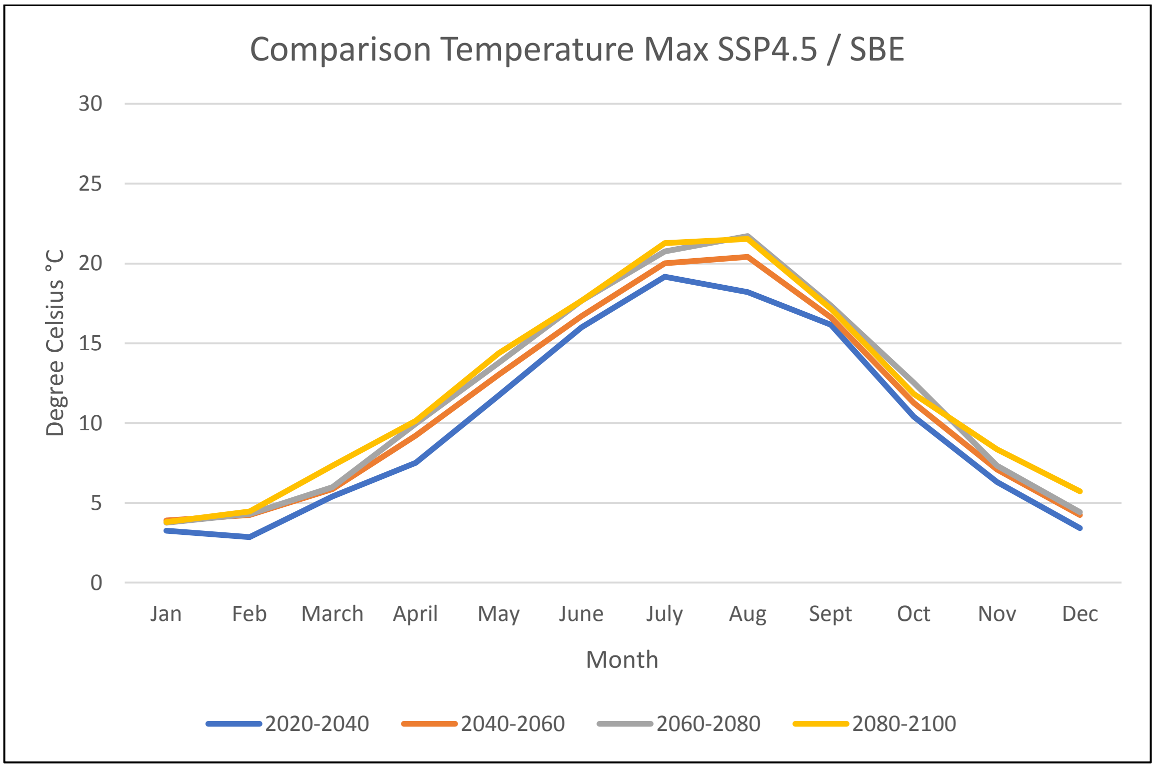

Figure 4.25: RCM Temperature maximum SSP4.5 – SBE

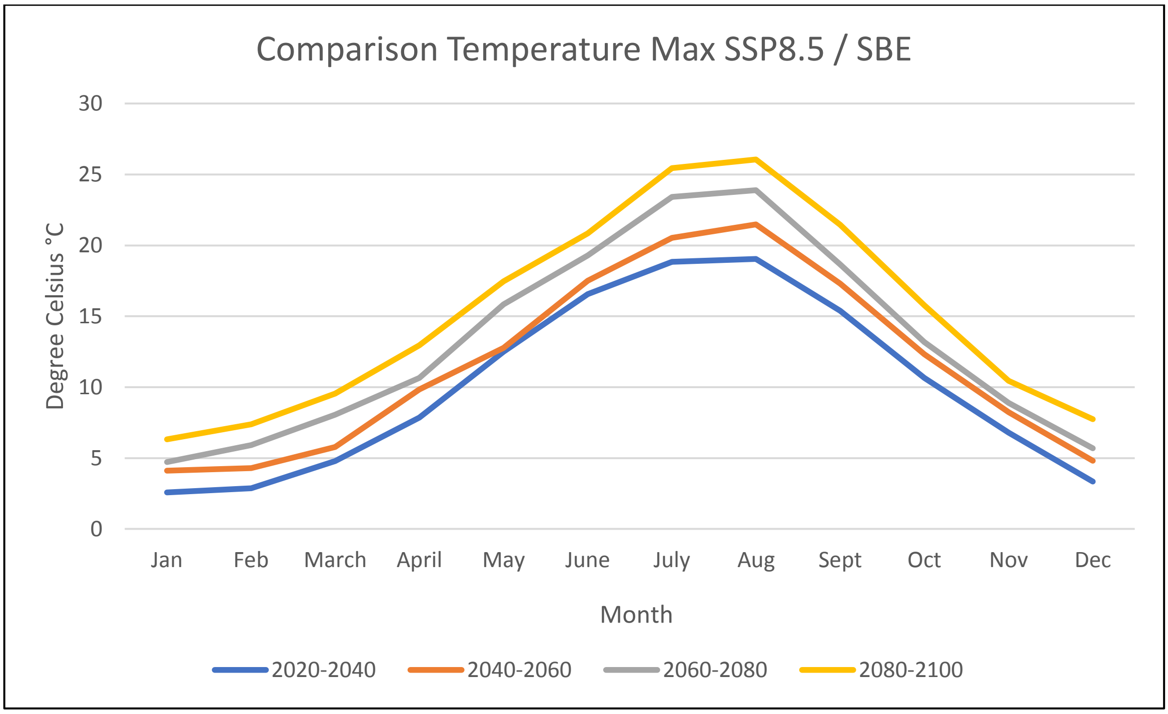

Figure 4.26: RCM Temperature maximum SSP8.5 – SBE

Climate Station Lugano (LUG)

Current temperature at station: Lugano is located in the southern part of Switzerland, in a region with a Mediterranean climate. The temperature maximum varies depending on the season, with the warmest months being June through August. During this time, the average high temperature is around 26°C, but temperatures can occasionally reach as high as 30°C or higher. In the winter months of December to February, the average high temperature is around 7-8°C, but temperatures can occasionally reach into the low 20s°C during mild spells.

In Lugano, the maximum temperature curves in Figure 4.20 show a very uniform picture and the average temperature in SSP8.5 also increases only slightly over the different intervals. Both models show that the maximum temperature in August is 28-32°C with the months July and August being the hottest. These are also currently the hottest temperatures in Lugano, with an average temperature of 26°C. The SSP4.5 shows an increase of this temperature to around 27-29°C , depending on the interval. The SSP8.5, on the other hand, shows an increase in the maximum temperature from 27°C in the interval 2020-2040 (blue curve) to 32°C in the interval 2080-2100 (yellow curve). Both models show the winter months of December to February as the coldest. This is also currently the case with maximum temperatures averaging 7-8°C. In the future, both models predict that temperatures will range between 8-10°C during these months.

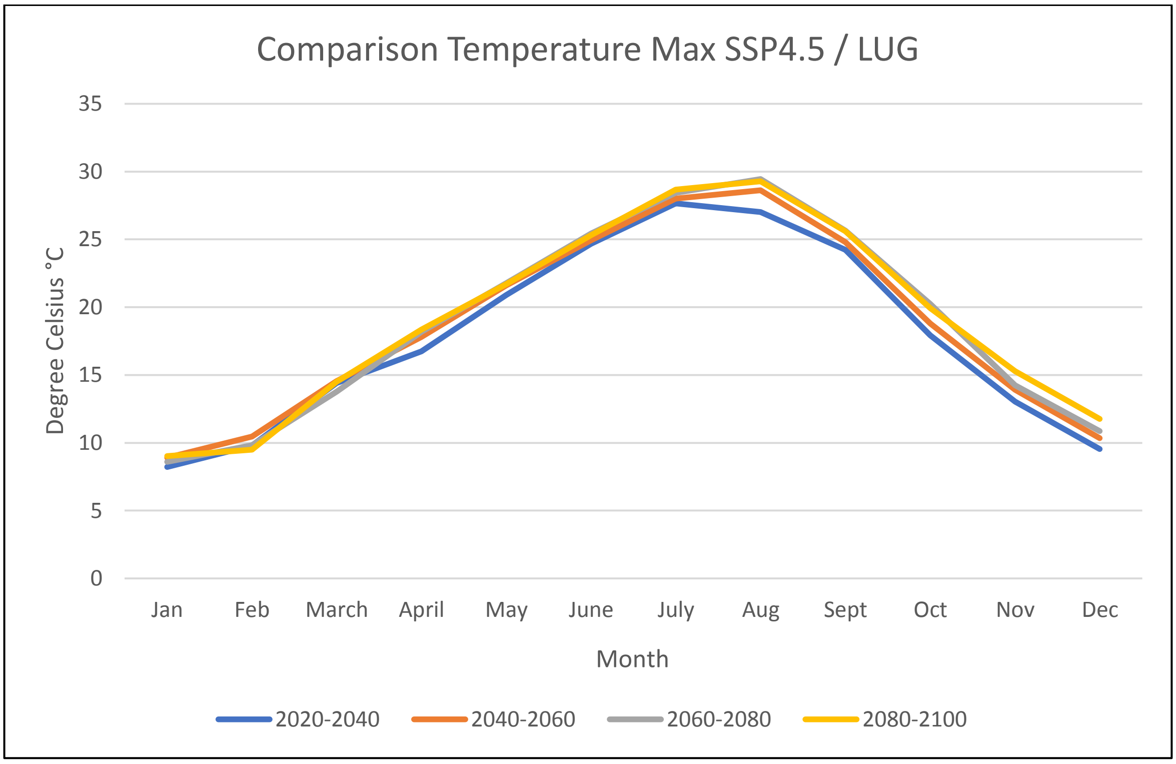

Figure 4.27: RCM Temperature maximum SSP4.5 – LUG

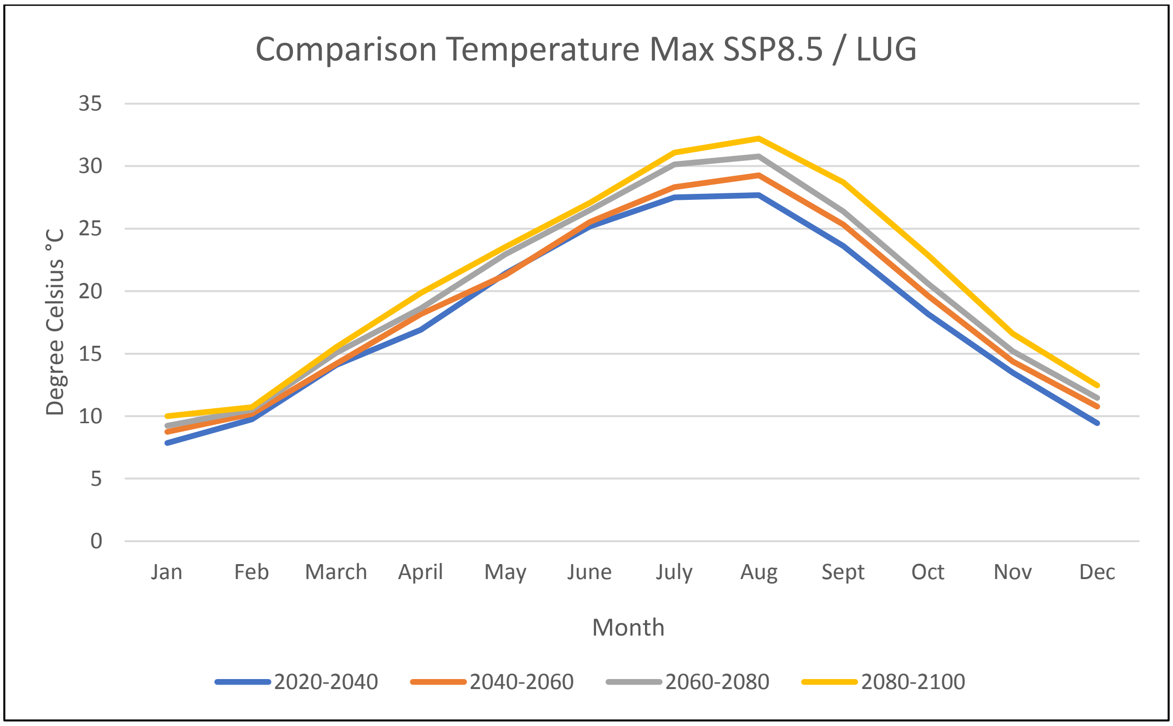

Figure 4.28: RCM Temperature maximum SSP8.5 – LUG

4.2.3 Temperature minimum

Climate Station Bern (BER)

Current temperature at station: The temperature minimum in Bern also varies throughout the year, with the coldest months typically being January and February. During these months, the average low temperature is around -3°C, but temperatures can occasionally drop as low as -10°C or lower. In the warmer months of June to August, the average low temperature is around 12-13°C. However, temperatures can still drop significantly at night, particularly in the higher elevations surrounding the city.

The curves in Figure 4.21 show the same progression in both climate models for the Bern station (as already in the temperature maximum models). In the SSP4.5 scenario, the curves are close to each other, while in SSP8.5 they are somewhat further apart, as greater warming is expected there. Therefore, the curves of the first interval (2020-2040, blue curve) are very similar in both models. For the following intervals, the SSP8.5 shows higher values. In summer, SSP4.5 calculates with temperatures between 15-17°C, while SSP8.5 does 15-21°C. In winter, SSP4.5 shows values around 1°C, SSP8.5 between 0-5°C. January and February are currently the coldest temperatures, which is also reflected in the models and will therefore remain so. The minimum temperature can currently show -3°C in winter. In the future, it will hover between 0-5°C (as already mentioned before). Therefore, both climate models show that a warming of the minimum temperature is to be expected. The same is true for the remaining months. The summer values are currently at 12-13°C and, according to SSP4.5 it will increase to 15-17°C and according to SSP8.5 to 15-21°C.

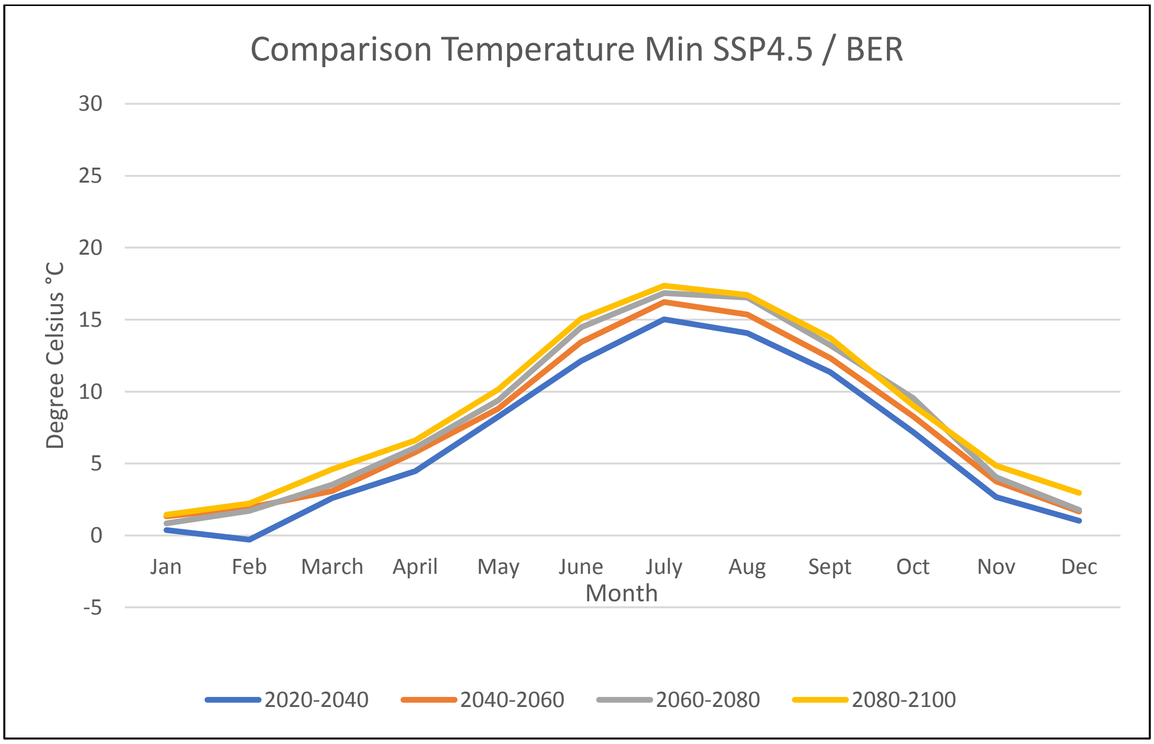

Figure 4.29: RCM Temperature minimum SSP4.5 – BER

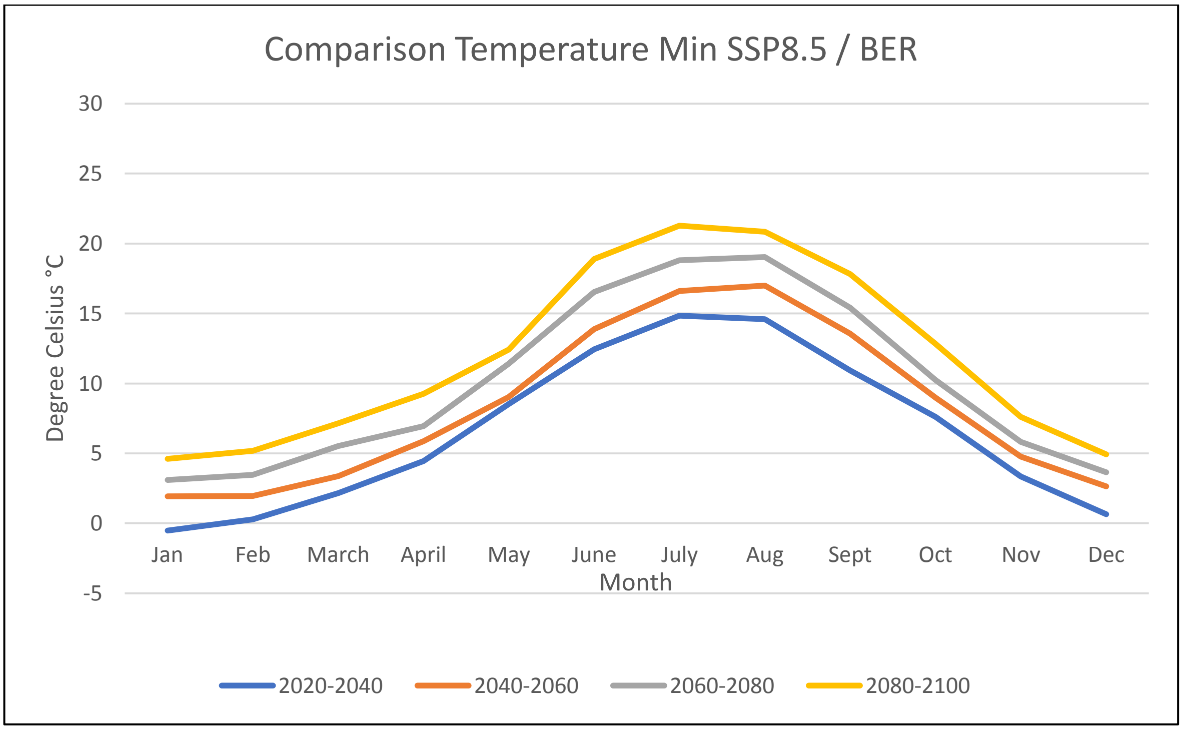

Figure 4.30: RCM Temperature minimum SSP8.5 – BER

Climate Station SAE (Säntis)

Current temperature at station: The temperature minimum in Säntis is much colder than the temperature maximum, with the coldest months being December through February. During this time, the average low temperature is around -10°C or lower, but temperatures can occasionally drop as low as -20°C or lower. In the summer months, the average low temperature is around -3°C.

It can also be observed in Figure 4.22 at the Säntis station that the two models draw the same curves, but SSP8.5 simply shows higher values. In July and August, minimum temperatures can be read from 5°C to 9°C in SSP4.5, while in SSP8.5 they are from 5°C to 14°C. In the coldest months December to February it is -7°C to -3°C (SSP4.5) and -8°C to -1°C (SSP8.5) respectively. Temperatures currently average minus 10°C in the cold months, which indicates that temperatures will rise in the future. A comparison of the current summer temperatures with the climate models reveals a major difference. While the current minimum temperatures are around -3, the two models assume a trend of 6°C upwards.

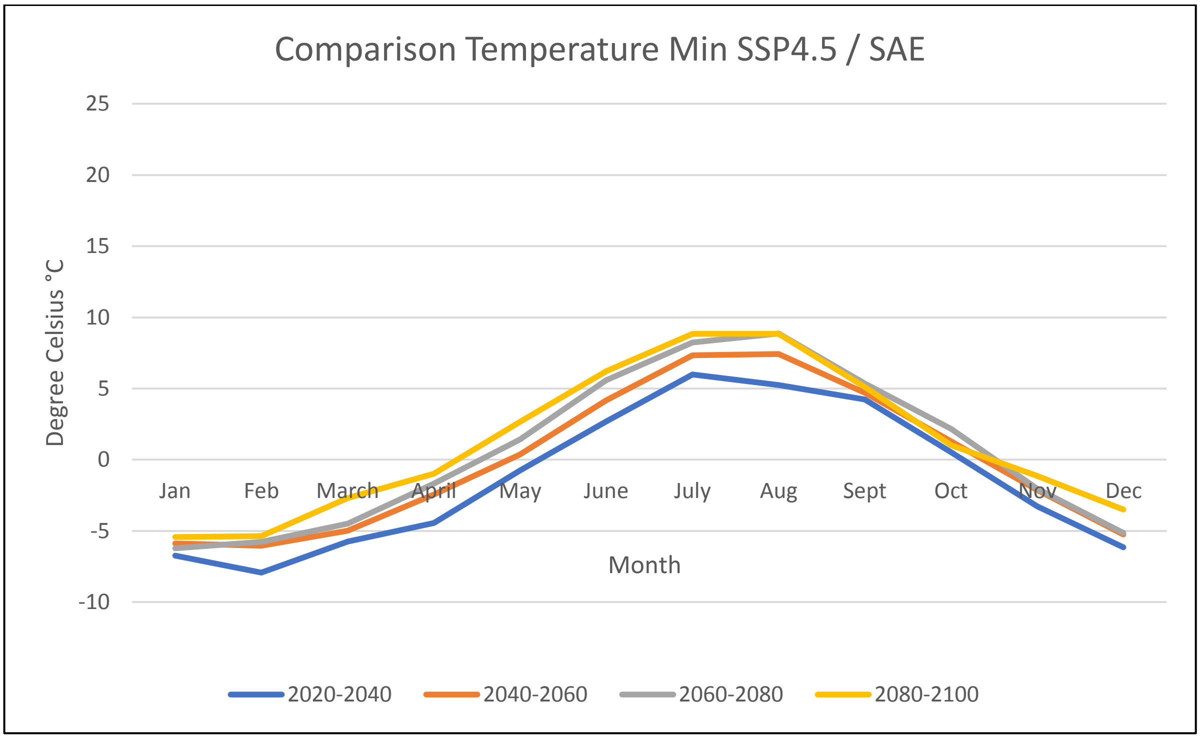

Figure 4.31: RCM Temperature minimum SSP4.5 – SAE

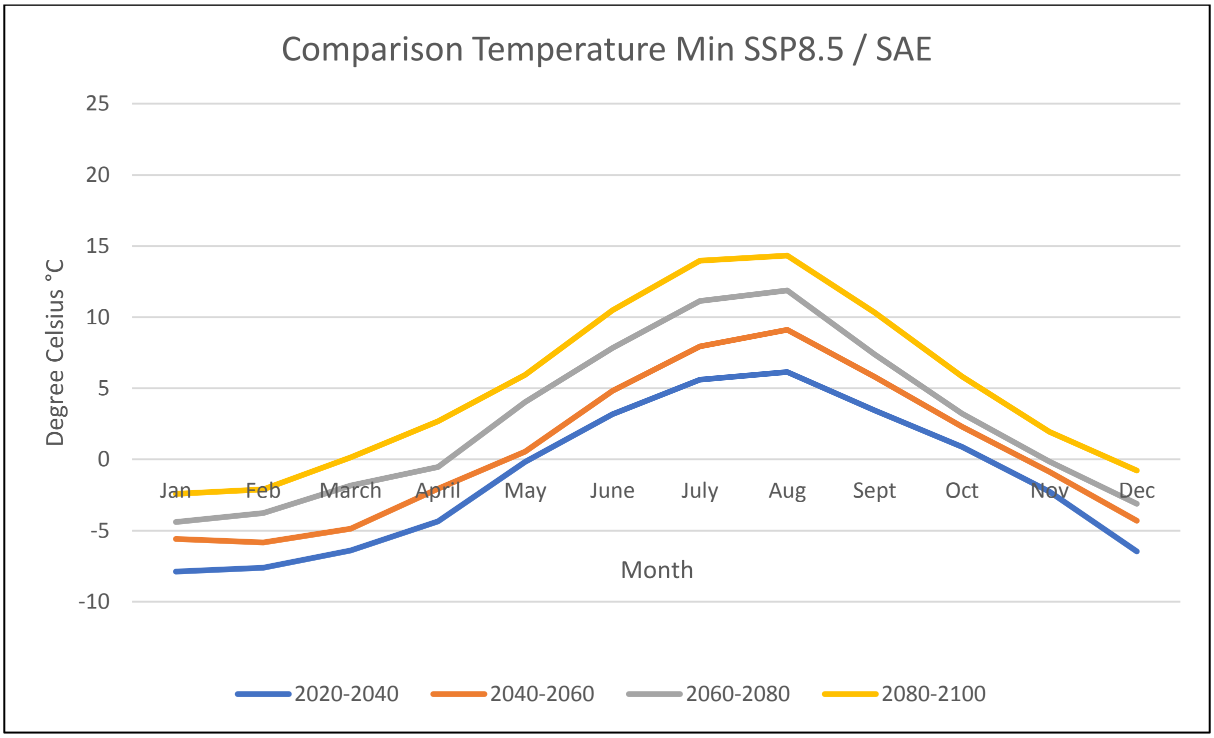

Figure 4.32: RCM Temperature minimum SSP8.5 – SAE

Climate Station S. Bernardino (SBE)

Current temperature at station: The temperature minimum in S. Bernardino is much colder than the temperature maximum, with the coldest months being December through February. During this time, the average low temperature is around -5°C or lower, but temperatures can occasionally drop as low as -15°C or lower. In the summer months, the average low temperature is around 5°C.

The two climate models in Figure 4.23 show almost identical patterns for the S. Bernardino station. In addition, the values in during the winter and the summer month are relatively close to each other. The minimum temperature in winter around -3°C and in summer is around 12°C. It should be mentioned that the SSP8.5 scenario shows higher temperatures with each interval. Therefore, it can be noted that SSP8.5 leads to higher temperature increases. Currently, average minimum temperatures of -5°C are recorded on the S. Bernardino in the winter months. In summer, they are around 5°C. This shows that temperatures will rise over the next few years.

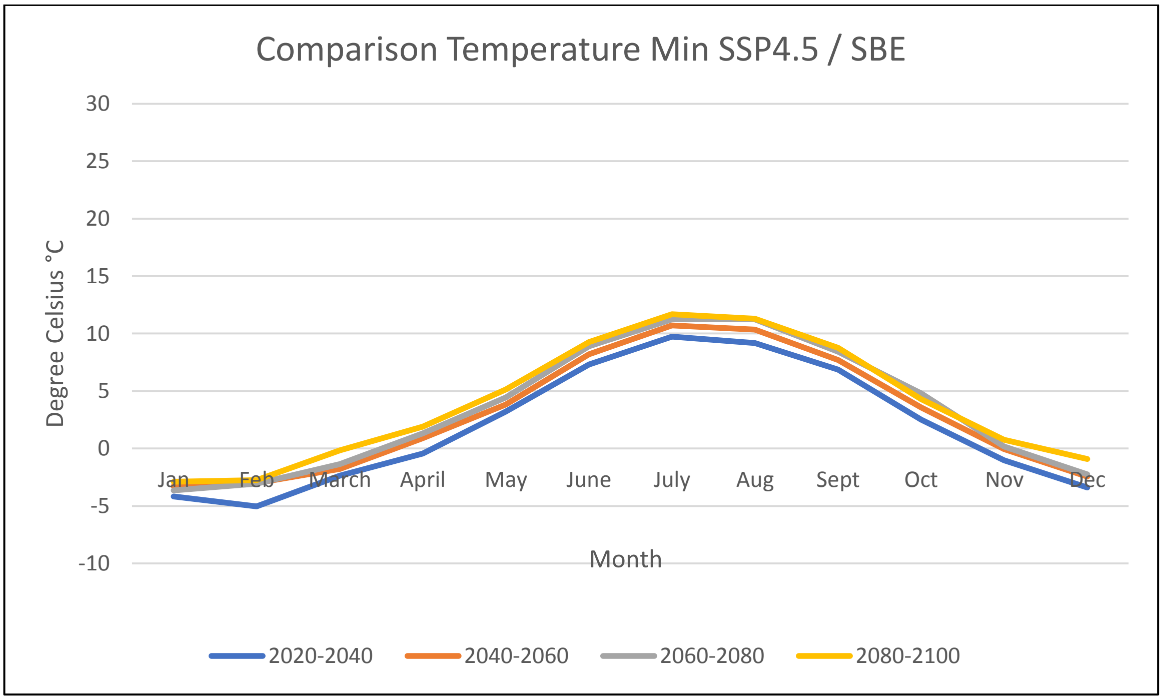

Figure 4.33: RCM Temperature minimum SSP4.5 – SBE

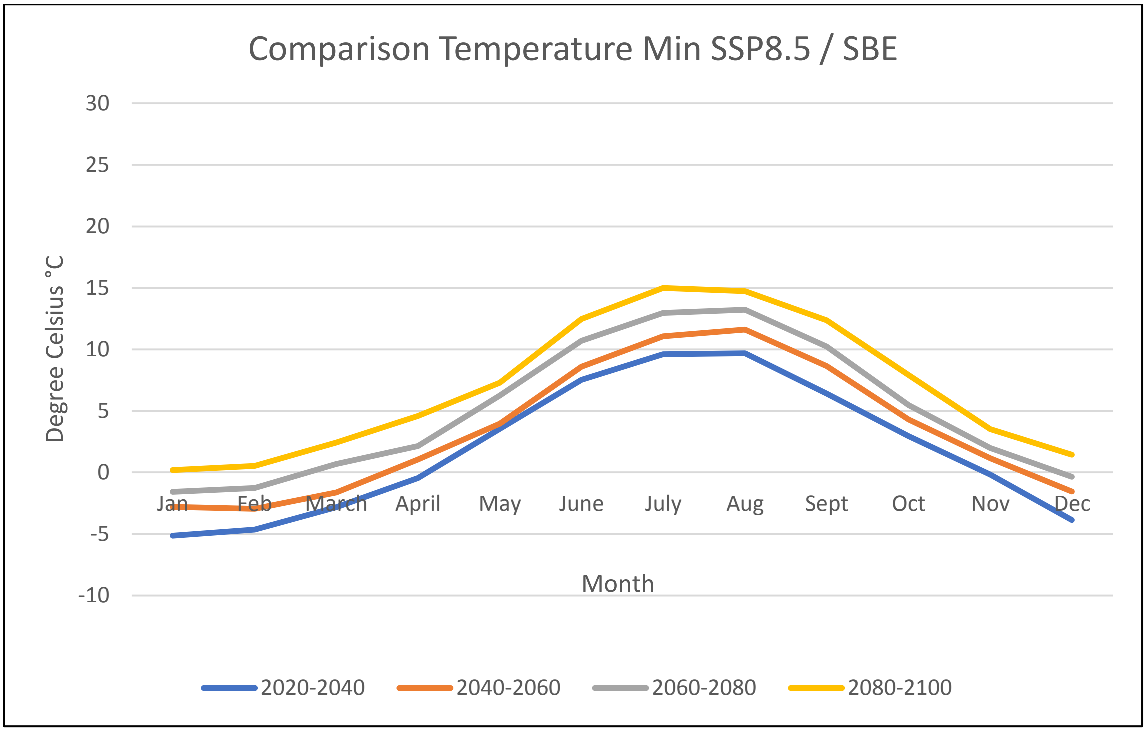

Figure 4.34: RCM Temperature minimum SSP8.5 – SBE

Climate Station Lugano (LUG)

Current temperature at station: The temperature minimum in Lugano also varies depending on the season, with the coldest months being December through February. During this time, the average low temperature is around 0-1°C, but temperatures can occasionally drop as low as -5°C or lower. In the summer months, the average low temperature is around 16°C.

The two climate models also show a uniform picture at the Lugano station (see Figure 4.24). Both scenarios have only little deviation over the different intervals, SSP8.5 as usual has greater differences between the individual intervals and shows higher temperatures than SSP4.5. Temperatures vary throughout the year from 4-6°C (winter months) to 19-24°C (summer months). The months December to February show the lowest values (winter), July and August the highest (summer). If these values are compared with the current measurements of 0-1°C in winter and 16°C in summer, it is seen that the average temperatures are increasing.

In summary, it can be said for all temperature models that the curves in the climate models are similar for the different time intervals. It is noticeable that in the SSP4.5 the curves are closer together, while in the SSP8.5 a higher temperature increase can be observed with each 20-year interval. It should therefore be noted that the climate models point to an increase in maximum and minimum temperatures by 2100.

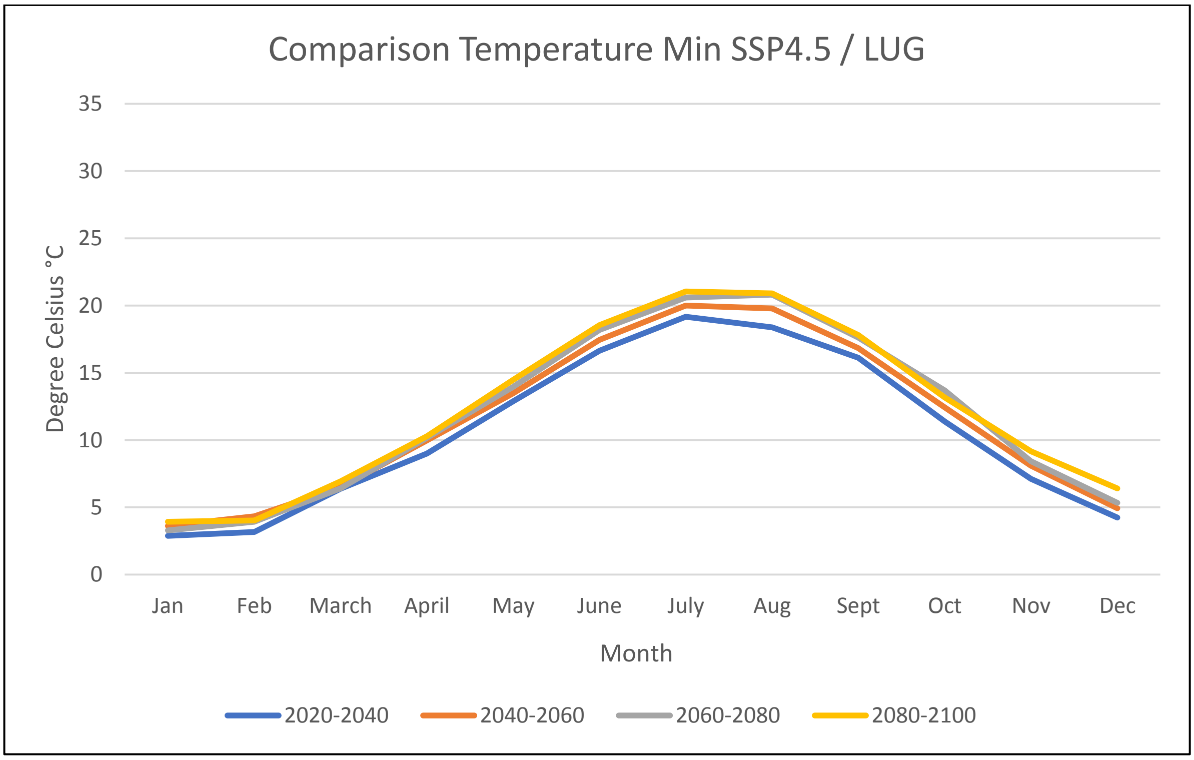

Figure 4.35: RCM Temperature minimum SSP4.5 – LUG

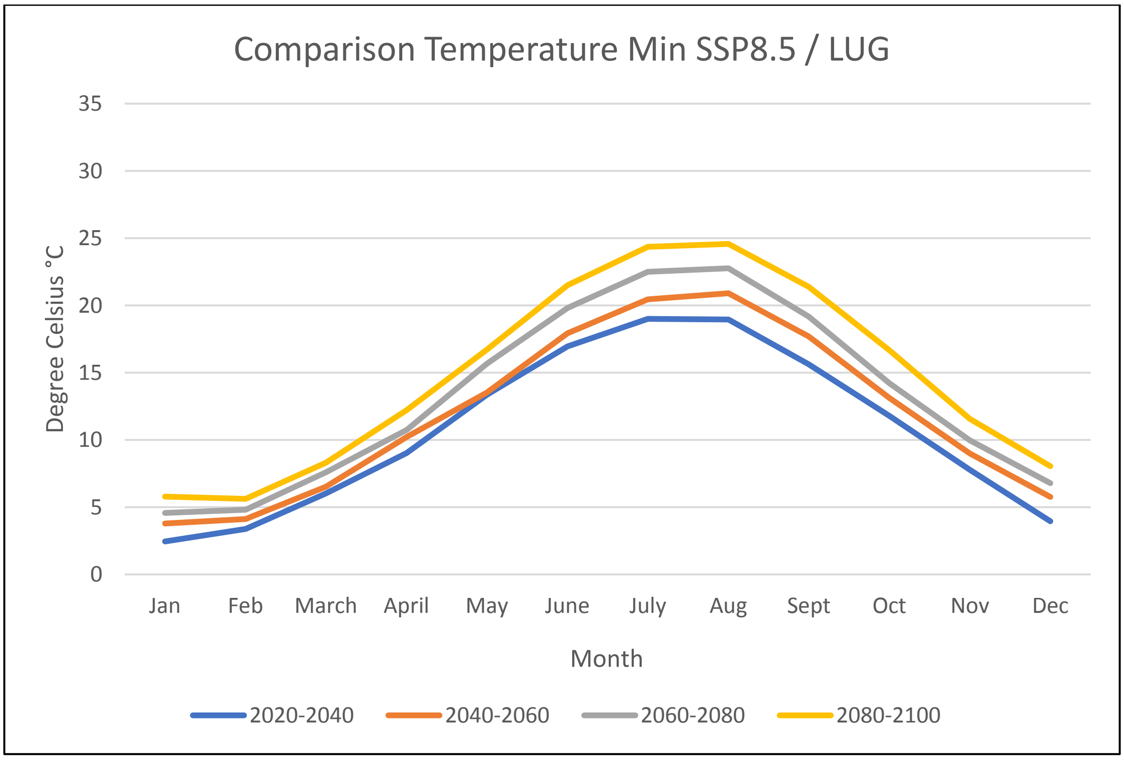

Figure 4.36: RCM Temperature minimum SSP8.5 – LUG

4.3 Reliability Assessment

The reliability assessment consists of three reliability tests, namely Linear Regression, Cronbach's Alpha and Probability Density Function. The reliability assessment is carried out to ensure that the regional climate model for Switzerland is reliable and consistent based on the SSP scenarios. Linear Regression and Cronbach's Alpha are conducted in SPSS Statistics 25 and Probability Density Function in Microsoft Excel 365.

4.3.1 Linear Regression and Cronbach's Alpha

Linear regression in SPSS can help you identify and quantify the relationship between a dependent variable and one or more independent variables. The monthly values of the years 2015 to 2021 are entered into SPSS and the function Linear Regression conducted. Cronbach's Alpha is a statistical measure of internal consistency reliability that can be used to assess the reliability and consistency of different data sets. Again, the monthly values of the years 2015 to 2021 are entered into SPSS and the function Cronbach's Alpha conducted (see Appendix F for screenshots of the procedures).

The R^2 value is a measure of the proportion of variance in the outcome variable that can be explained by the predictor variables. It ranges from 0 to 1, with higher values indicating that a larger proportion of the variance in the outcome variable is explained by the predictor variables. In general, it is assumed that an R^2 greater than or equal to 0.4 can be considered significant ($R^2 \geq 0.4$, Sig).

Cronbach's alpha is a measure of internal consistency reliability, which is used to assess the extent to which a set of data measures the same construct. Alpha ranges from 0 to 1, with higher values indicating greater internal consistency. In general, the interpretation of Cronbach's alpha values is as follows:

Alpha Score	**Level of Reliability**
0.0 – 0.2	Less Reliable
0.2 – 0.4	Rather Reliable
0.4 – 0.6	Quite Reliable
0.6 – 0.8	Reliable
0.8 – 1.0	Very Reliable

In this work the aim is a reliable internal consistency meaning an alpha greater than or equal to 0.6 ($a \geq 0.6$).

First, the results for precipitation should be interpreted. The outputs are shown in Table 4.1 and show low values for linear regression indicating that only a small proportion of the variance in the outcome variable is explained by the predictor variables. The Cronbach's Alpha results show Alpha between 0.1 to 0.4 and therefore also do not show the desired values. From the data of the two reliability tests, it can be deduced that scenario SSP4.5 has a higher reliability, even if it must of course be stated on the outset that the result is not reliable.

Table 4.1: Linear Regression and Cronbach's Alpha Precipitation

Precipitation			
Climate Station	**SSP Scenario**	**Linear Regression ($R^2 \geq 0.4$, Sig)**	**Cronbach Alpha (a ≥ 0.6)**
Bern (BER)	SSP4.5	0.044	0.345
	SSP8.5	0.033	0.345
Säntis (SAE)	SSP4.5	0.116	0.438
	SSP8.5	0.005	0.116
S. Bernardino (SBE)	SSP4.5	0.070	0.419
	SSP8.5	0.021	0.254
Lugano (LUG)	SSP4.5	0.020	0.226
	SSP8.5	0.024	0.204

There are several factors that could contribute to the low results in the reliability tests. The reasons should be evaluated as follows. First, there could be limitations in the predictors. CMIP6 data can be a valuable resource for climate modelling, but it may not capture all the complex processes that contribute to precipitation patterns in Switzerland, particularly in an alpine region with complex terrain. The resolution of the data may also be too coarse to capture local precipitation variations. Additionally, other factors, such as land use changes and human activities, can also impact precipitation patterns in the region, and these may not be fully accounted for in the predictor data. Second, the structure and assumptions of the precipitation model may also be a factor in the low reliability scores. For example, the model may does not account for local features of the landscape, such as elevation changes or regional atmospheric circulation patterns. This could also contribute to low reliability scores. Further, the observational data used to generate and validate the model may not be complete, particularly if there are gaps in the data or if the station network does not capture all the variability in precipitation patterns. This could lead to errors or biases in the model output. Last, precipitation patterns in Switzerland can be highly variable, both over time and across different regions. This inherent variability may make it difficult to build a reliable model, particularly if the model does not capture all the relevant factors that contribute to this variability.

In a next step, the output of the temperature models are explained. The following two tables show the output obtained for Linear Regression and Cronbach's Alpha. Both tables show similar and solid results. First, the output for temperature maximum is discussed. Table 4.2 contains the output for temperature maximum. Bern achieves values above 0.8 for R^2 and 0.9 for Cronbach's alpha in both scenarios. For the Säntis station, the output shows 0.7 for SSP4.5 or 0.6 for SSP8.5 for R^2. And it shows over 0.9 in both scenarios for Alpha. S. Bernardino shows similar outputs for both scenarios. For R^2, the values are above 0.8 and Alpha above 0.9. Lugano shows the highest reliability with results for both scenarios and both tests above 0.9. Alpha Scores over 0.8 can be interpreted as very reliable. Therefore, the values of all four stations can be considered consistent and reliable. Overall, the outputs for SSP4.5 show slightly better results.

Table 4.2: Linear Regression and Cronbach's Alpha Temperature maximum

Temperature maximum			
Climate Station	**SSP Scenario**	**Linear Regression ($R^2 \geq 0.4$, Sig)**	**Cronbach Alpha ($a \geq 0.6$)**
Bern (BER)	SSP4.5	0.841	0.954
	SSP8.5	0.810	0.946
Säntis (SAE)	SSP4.5	0.719	0.917
	SSP8.5	0.670	0.900
S. Bernardino (SBE)	SSP4.5	0.818	0.938
	SSP8.5	0.819	0.939
Lugano (LUG)	SSP4.5	0.920	0.979
	SSP8.5	0.913	0.977

The outputs for the minimum temperature tests are shown in Table 4.3 and draw a similar picture. Bern has values over 0.8 for R^2 and over 0.9 for Cronbach's Alpha. Säntis receives R^2 results of 0.7 and 0.6 for SSP4.5 and SSP8.5, respectively. For the S. Bernardino station, the tests show results of over 0.8 for R^2 and 0.9 for Alpha. Lugano also has the highest reliability for minimum temperatures, with over 0.9 in both tests and for both scenarios. When comparing the outputs between the two scenarios, SSP4.5 shows slightly higher results and can therefore be considered a more reliable scenario.

Table 4.3: Linear Regression and Cronbach's Alpha Temperature minimum

Temperature minimum			
Climate Station	**SSP Scenario**	**Linear Regression ($R^2 \geq 0.4$, Sig)**	**Cronbach Alpha (a ≥ 0.6)**
Bern (BER)	SSP4.5	0.884	0.968
	SSP8.5	0.877	0.966
Säntis (SAE)	SSP4.5	0.736	0.923
	SSP8.5	0.697	0.910
S. Bernardino (SBE)	SSP4.5	0.864	0.962
	SSP8.5	0.852	0.959
Lugano (LUG)	SSP4.5	0.928	0.981
	SSP8.5	0.921	0.979

4.3.2 Probability Density Function

Microsoft Excel 365 is used for the Probability Density Function (PDF) because it provides some effective functions to calculate the probability density function of a variable. To calculate the PDF of a given set of data using Microsoft Excel, the NORM.DIST function in combination with the AVERAGE and STDEV functions is used. The detailed procedure of the calculations is described in appendix G. Hereafter, the line diagrams are shown and interpreted. The curves of the three data sets are displayed in different colors as described below.

Data	Colour
Observation (raw)	**Blue**
SSP4.5	**Orange**
SSP8.5	**Grey**

The x-axis of the chart represents the precipitation (in mm) or temperature (°C), respectively. The y-axis of the chart represents the probability density. The curves show that all data sets lead to the same PDF (0.4 on y-axis). If the bars are of equal height, it means that the probability density is the same for each range of values. The shape of the curve in the bar chart depends on the underlying probability distribution. For example, a normal distribution will have a bell-shaped curve, while a uniform distribution will have a flat curve. The generated diagrams all have a bell-shaped curve and therefore fall under normal distribution. The three curves should have the same shape, because it shows that they are all drawn from the same probability distribution. This means that the three data sets are related in some way, either through a common underlying process or through some other factor that affects all of the data sets in a similar way. If the curves have different shapes, it suggests that they are drawn from different probability distributions, which may reflect differences in the underlying processes or factors that affect the data. In this case, it may be necessary to further investigate the differences in the data sets and their sources to better understand the underlying causes of the differences in the curves. In the following, the peaks are considered in particular, as they can be used to conclude whether the rainfall or temperature will increase or decrease in the future.

Figure 4.25, Figure 4.26, Figure 4.27, and Figure 4.28 show the PDF curves for precipitation and are presented on the next page. The Bern and S. Bernardino stations show uniform curves. This indicates that the predictors are accurately capturing the underlying patterns in the original data. This suggests that the predictions are reliable and may be useful for making decisions. On the other hand, in the diagrams of Säntis and Lugano, the curves of the observed data show a different shape than those of the created scenarios. This can indicate a variety of issues such as incorrect predictor variables, inappropriate model selection, or inadequacy of the model assumptions. Therefore, the predictors and the procedure for creating the rain models were checked. The predictors seem to be accurate and since the other two stations (Bern and S. Bernardino), which are generated in the same way, show solid results, it is assumed that the models can still be used. Bern has uniform curves. The observation data (blue curve) and SSP4.5 (orange) and SSP8.5 (grey) data draw their peak at the same amount of precipitation, from which it can be concluded that the amount of rainfall remains the same for this station. Säntis shows a deviation in the shape of the curves between the observed data and the compiled data. The shift of the peak to the left indicates that there will be less rain in the future under the chosen scenarios. Even at Lugano, the curves do not show the same shape. The peak is shifting slightly to the left, which means that less rain can be expected in the future. For the S. Bernardino station, the curves again paint a uniform picture. The peak shifts to the right compared to the observational data. This means that the models show a rise in precipitation, meaning that it will rain more in future.

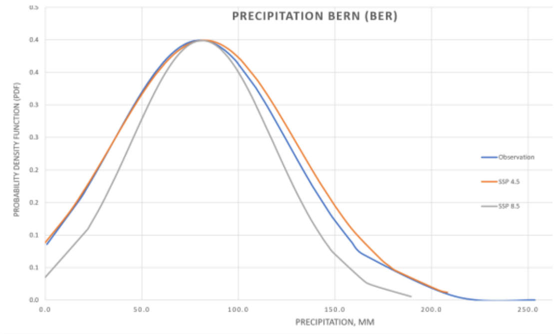

Figure 4.37: PDF Precipitation Bern

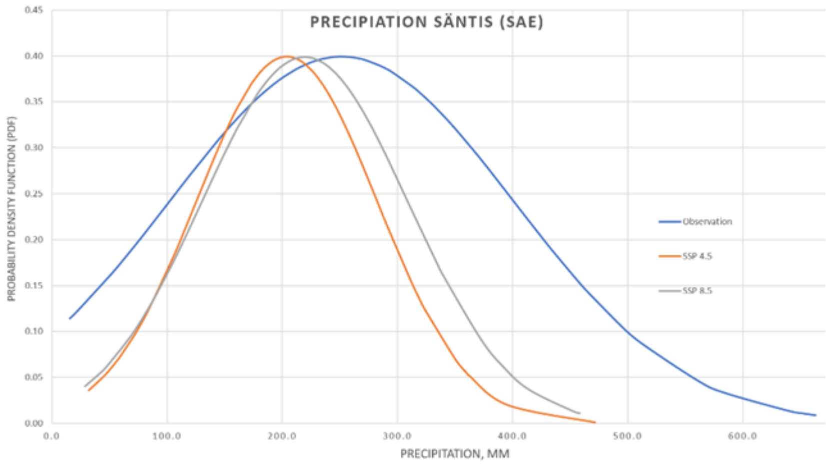

Figure 4.38: PDF Precipitation Säntis

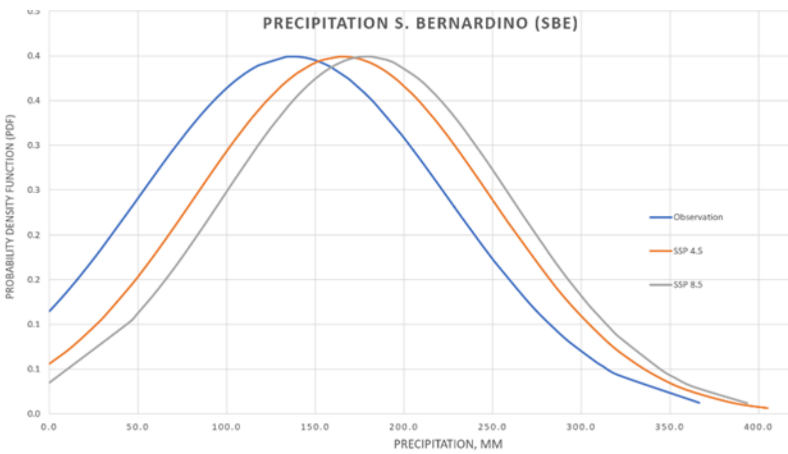

Figure 4.39: PDF Precipitation S. Bernardino

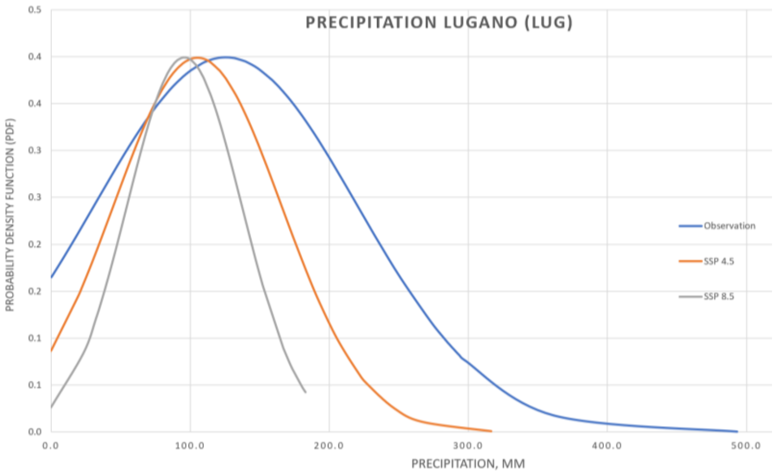

Figure 4.40: PDF Precipitation Lugano

Figure 4.29, Figure 4.30, Figure 4.31, and Figure 4.32 illustrate the Temperature maximum charts and are shown on the next page. The curves show the same shape, which indicates that the predictors are accurately capturing the underlying patterns in the original data. This suggests that the predictions are reliable and may be useful for making decisions. For the station Bern the curves SSP4.5 and SSP8.5 show a minimal deviation to the right compared to the observation data. This shows that the maximum temperature will be slightly higher in both scenarios. The Säntis station shows a similar picture. The peak of the two scenarios shifts slightly to the right (more than at Bern), which means that an increase in the maximal temperature is to be expected. For Lugano, the peaks of the curves lie exactly on top of each other. This indicates that the maximum temperature will remain the same in both scenarios. The S. Bernardino station shows a large deviation of the peaks. The peak of the scenarios is much further to the left than that of the observation data. This leftward shift indicates a strong decrease in maximum temperature.

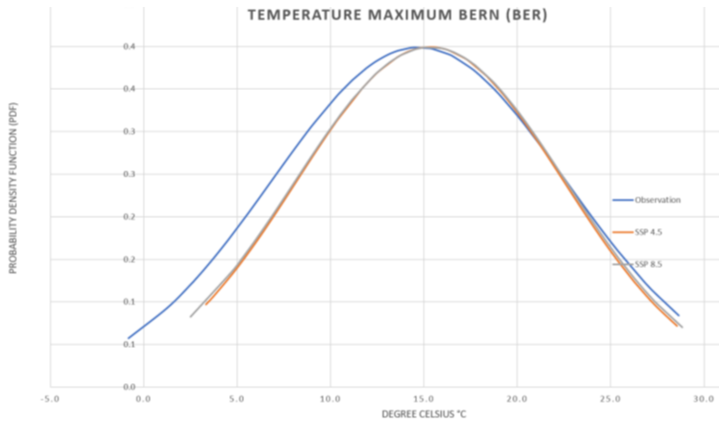

Figure 4.41: PDF Temperature maximum Bern

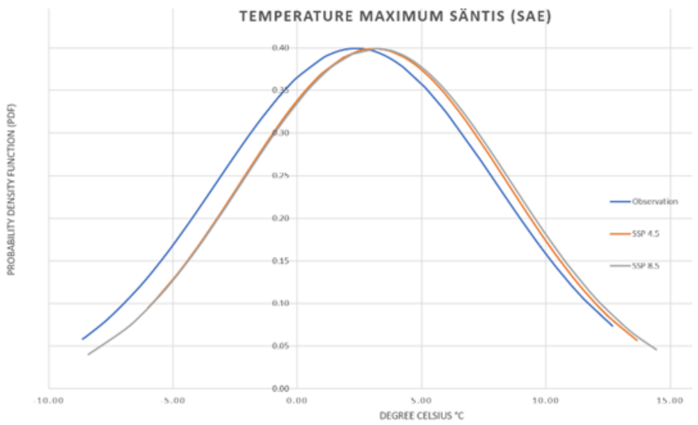

Figure 4.42: PDF Temperature maximum Säntis

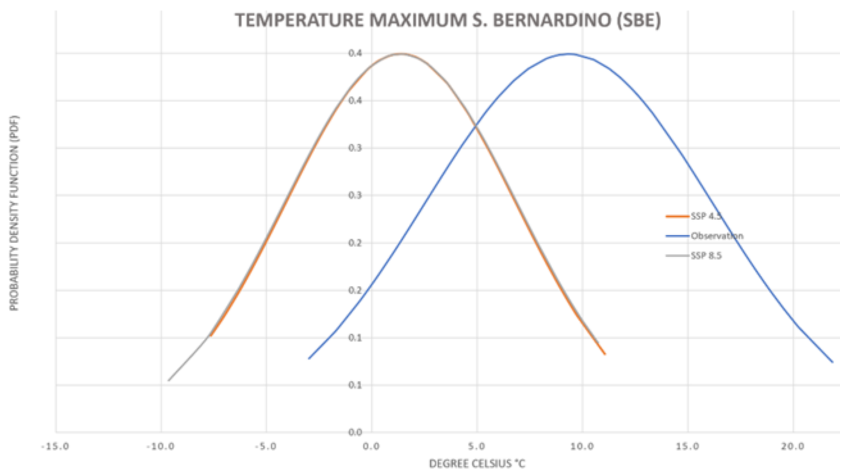

Figure 4.43: PDF Temperature maximum S. Bernardino

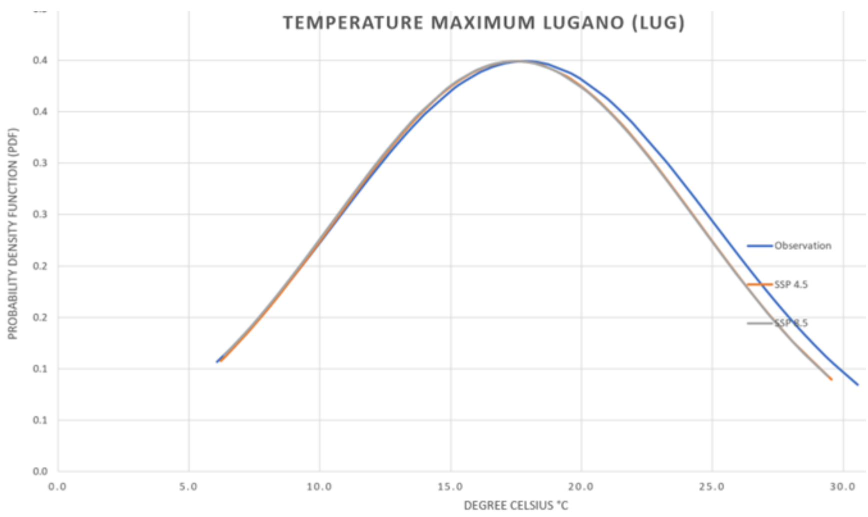

Figure 4.44: PDF Temperature maximum Lugano

The curves in the Temperature minimum charts show the same shape as in Temperature maximum, which indicates that the predictors are accurately capturing the underlying patterns in the original data. This suggests that the predictions are reliable and may be useful for making decisions. Figure 4.33, Figure 4.34, Figure 4.35 and Figure 4.36 show the PDF for temperature minimum and are presented on the next page. For the Bern station, the diagram shows that the minimum temperature increases slightly in the scenarios. The same applies to the Säntis station. The peaks of the scenario curves shift slightly to the right, indicating an increase in the minimum temperature. Lugano shows a minimum rightward shift, which means that the minimum temperature remains the same for both scenarios. S. Bernardino, on the other hand, shows a slightly larger rightward shift, which means that an increase in the minimum temperature can be expected in both scenarios.

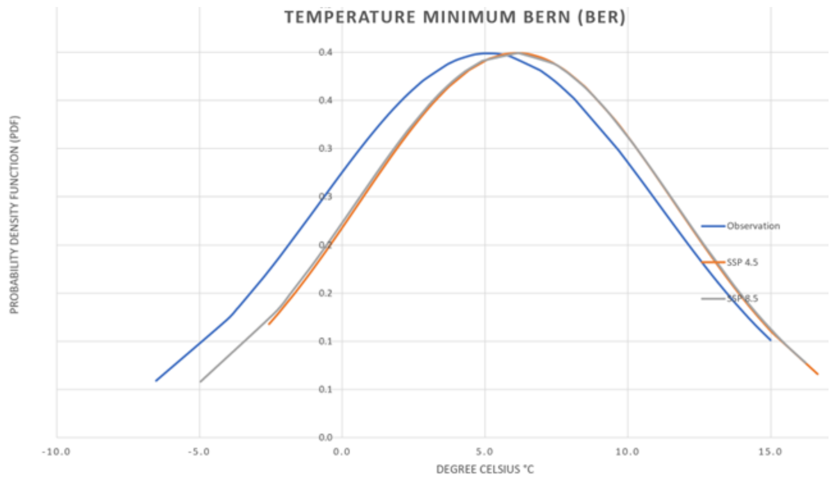

Figure 4.45: PDF Temperature minimum Bern

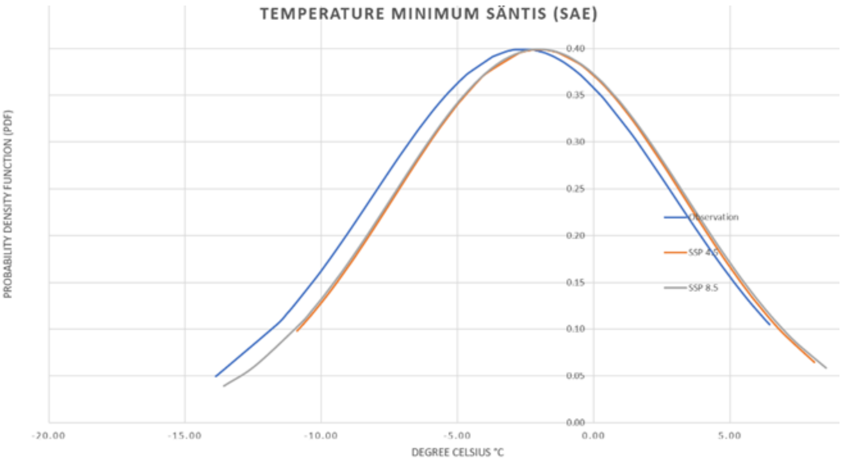

Figure 4.46: PDF Temperature minimum Säntis

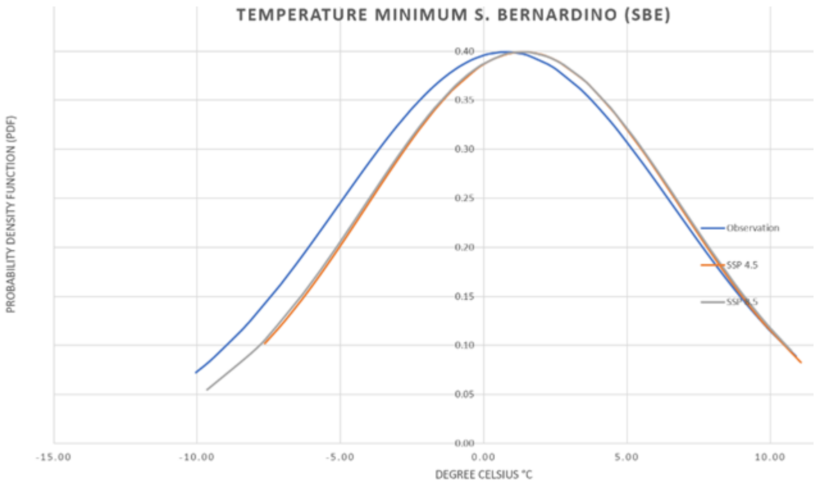

Figure 4.47: PDF Temperature minimum S. Bernardino

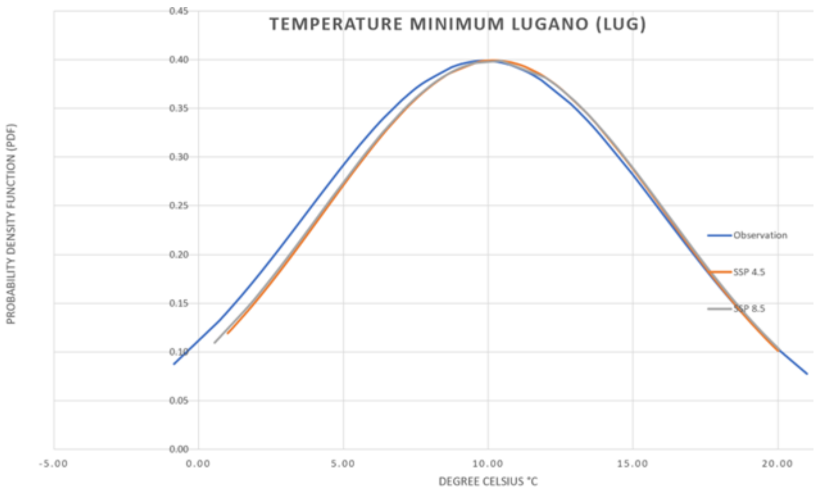

Figure 4.48: PDF Temperature minimum Lugano

4.4 Recommend RCM scenario

As mentioned in the introduction, the more likely and reliable SSP scenario will be recommended to serve as an important early warning signal to decision makers and the public. According to the reliability tests, SSP4.5 is the more suitable scenario for future climate change projection of Switzerland. The SSP4.5 scenario, also known as the "medium stabilization scenario," assumes that global greenhouse gas emissions will peak around 2040 and decline thereafter. However, this scenario still leads to significant warming (Climatedata, 2022). From the temperature models generated it is evident that the temperatures increase by 2-4°C by mid-century and 3-7°C by the end of the century. These results are confirmed in a recent study by Kotlarski et al. (2023), who projected changes in temperature and precipitation over Switzerland for the 21st century using a high-resolution climate model. For precipitation, the study predicts a seasonal shift of precipitation amounts from summer to winter over most parts of the domain. All seasons and sub-domains are expected to have an increase in daily precipitation. However, summer will see a drop in the number of wet days. Accordingly, simulations and/or places with a large seasonal mean warming often indicate a stronger decrease in precipitation. The anticipated temperature change in the summer is inversely connected with the precipitation change. For winter, however, there is a noticeable positive link between changes in temperature and amounts of precipitation. In addition to other signs, the anticipated climatic changes will have a significant impact on snow cover, which will generally decrease save for very high elevation locations (Kotlarski *et al.*, 2023). The latest IPCC report, AR6 Synthesis Report (SYR), further emphasize that a global warming at 2°C or above will lead to agricultural and ecological droughts in Europe. Europe has to take water management measures as there will be too little rain in the summer months (IPCC AR6 SYR, 2023).

This chapter discusses the impact of the temperature increase on the regions of the four stations. Since the temperature models received reliable outputs in the reliability assessments and studies came to the same conclusion, the models are considered reliable. In addition, an attempt is made to derive the amount of rainfall from the temperature increase and to evaluate the effects of precipitation. As the precipitation models did not produce significant results in the reliability tests, the results are not included in the following discussion. The focus of the explanations is on the impacts that are to be expected as a result of the changes in temperature and precipitation patterns. For each of the impacts, instructions for action are given to the Swiss government, whith which it can mitigate or eliminate the impact.

Climate Station Bern (BER)

Bern is the capital city of Switzerland and is located in the central part of the country, on the Swiss plateau. The city has a humid continental climate, which is characterized by relatively warm summers and cold winters. The temperature models show for Bern a temperature increase by 2-4°C by mid-century and 3-7°C by the end of the century. The International Energy Agency (IEA) expects in northern Switzerland an increase in heavy precipitation during the winter. It is anticipated that the intensification of precipitation patterns during the winter may increase the risk of floods by causing more runoff in the winter and early spring (particularly in low-altitude regions)(IEA, 2022). The Figure 4.37 shows that Switzerland has been at medium risk of flooding for the past two decades. This risk is likely to increase in the future. Floods can have several effects on Bern, a city with a historical old town. Floods can damage roads, bridges, buildings, and other critical infrastructure. This can disrupt transportation, communication, and access to services. Flood damage can be costly to repair and can also result in business interruptions and lost productivity. This can have significant economic impacts on the city and region. Floodwaters can carry pathogens and contaminants that can pose health risks to people exposed to them. Floods can also result in increased risks of waterborne diseases and mold growth. In severe floods, residents may need to be temporarily or permanently displaced from their homes. This can be traumatic and can result in long-term impacts on individuals and communities. Floods can also have significant impacts on the environment, including erosion, sedimentation, and habitat destruction. This can affect wildlife, ecosystems, and water quality. Therefore, the government should establish protective measures against floods at an early stage, especially in the city centre and inhabited areas. Rainwater gutters and collection basins will play an important role in the future. The government can invest in flood protection measures, such as levees, flood walls, and detention basins, to prevent flooding in areas that are prone to flooding. These measures can help to protect property and reduce the risk of damage to infrastructure. Further the government should start to implement land use planning measures, such as zoning regulations and building codes, to prevent development in flood-prone areas and to require new buildings to be designed to withstand flooding. In the summer month, the overall number of wet days is expected to shrink and possibly lead to drier summers (IEA, 2022). According to Figure 4.37 the risk of drought in Switzerland has been considered low for the last twenty years. Nevertheless, the government should already implement measures to combat drought, as rising temperatures and dry summers mean that drought is likely in the future. Drier conditions can increase the risk of wildfires, especially in areas with dry vegetation. This can pose a significant threat to public safety and property. Drier conditions can lead to reduced water availability, which can have significant impacts on agriculture, tourism, and other sectors that rely on water. Water scarcity can also affect public health and hygiene. Moreover, drier conditions can lead to crop failures and reduced yields in agriculture. This can have economic impacts on farmers and food prices for consumers. Further, drier conditions can increase the risk of heat-related illnesses and respiratory problems due to dust and air pollution. This can be especially dangerous for vulnerable populations like the elderly and those with pre-existing health conditions. Last, drier conditions can also have significant impacts on ecosystems, including reduced biodiversity, increased soil erosion, and changes in plant and animal distributions. To address these issues the government must improve water management and promote drought-resistant agriculture. In urban areas, the government can implement measures to reduce water demand, such as promoting water-efficient fixtures and appliances, implementing water-saving policies, and investing in water recycling and reuse systems. Further, the governments should invest in green infrastructure, such as green roofs, rain gardens, and permeable pavements, that can help to reduce stormwater runoff and improve water quality. In agricultural areas, governments can implement measures to improve water efficiency, such as promoting precision irrigation technologies, improving soil management practices, and investing in water storage and distribution systems. However, the fall in the energy demand for heating and an increase for cooling may also has a positive effect including a drop in the consumption of oil-based products and an increase in the use of electricity. Given the total energy consumption profile of the nation, it is expected that the decrease in heating demand will outweigh the rise in cooling demand, resulting in an overall increase in welfare and a reduction in carbon emissions (IEA, 2022).

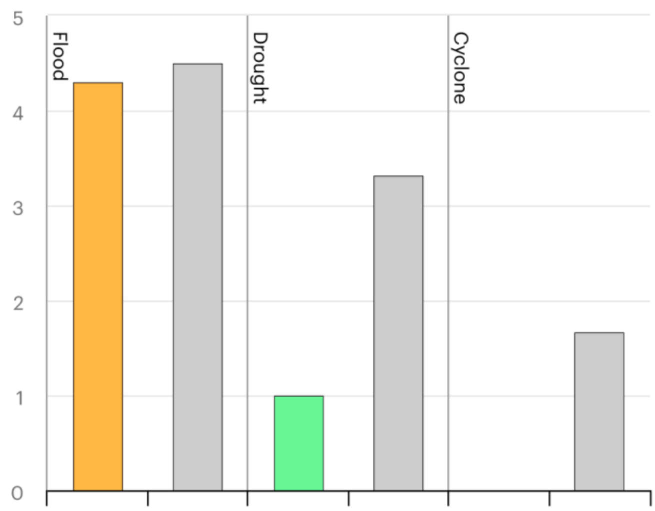

Figure 4.49: Level of floods, drought and tropical cyclones in Switzerland, 2000-2020 (IEA, 2022)

Climate Station Säntis (SAE)

Säntis is a mountain peak located in the eastern part of Switzerland. It is situated in the Alpstein range of the Appenzell Alps, at an altitude of 2,502 meters above sea level. The IPCC observed a mountain surface air temperature warming in the Alps of at an average rate of 0.3°C until the end of the decade (IPCC, 2022). This is consistent with the temperature models for Säntis, which show an increase of around 1°C per 20-year interval. The temperature models show for Bern a temperature increase by 3-4°C by mid-century and 3-6°C by the end of the century. According to the IPCC, the Alps warming has been found to be more pronounced in summer and spring (IPCC, 2022). Future projections of annual precipitation indicate increases of the order of 5 to 20% over the 21st century in the mountain areas like the Alps. Increases in winter precipitation extremes are projected in the Alps by the IPCC (2022). A study covering the Swiss Alps showed that the number of rain-on-snow events may increase by 50%, with a regional temperature increase of 2°C to 4°C, and decrease with a temperature rise exceeding 4°C (IPCC, 2022). Figure 4.38 shows a summary of the changes which must be expected. Warmer temperatures can cause permafrost to thaw, which can destabilize slopes and increase the risk of landslides. This can pose a threat to infrastructure and communities in mountainous areas. As temperatures rise, the snow line may move higher up the mountains, resulting in less snow and fewer avalanches. This can have implications for winter sports and tourism, as well as for avalanche risk management. Warmer temperatures can also cause glaciers to melt, which can increase the risk of floods and landslides downstream. This can have significant impacts on communities and infrastructure in the valleys. Further, infrastructure systems in mountain areas, such as roads, railways, and hydropower plants, may be affected by changing weather patterns and the increased risk of natural hazards, such as landslides and floods. This can pose significant challenges for the maintenance and operation of these systems. The government should work with communities and stakeholders to develop and implement adaptation strategies that address the specific impacts of climate change in the Alpine region. This can include measures to protect infrastructure, manage natural hazards, and promote sustainable land use practices. Governments should strengthen infrastructure and building codes to ensure that they are designed to withstand the impacts of climate change, such as increased flood risk and landslides. Further, the government could invest in research and monitoring to better understand the impacts of climate change on the Alpine region and to develop effective adaptation measures. This can include research on natural hazards, ecosystem dynamics, and the social and economic impacts of climate change. On the other hand, the high mountains are probably becoming a well-liked vacation spot as heatwaves grow longer and more intense. In general, summer tourism potential is rising while winter tourism is suffering from declining snow reliability.

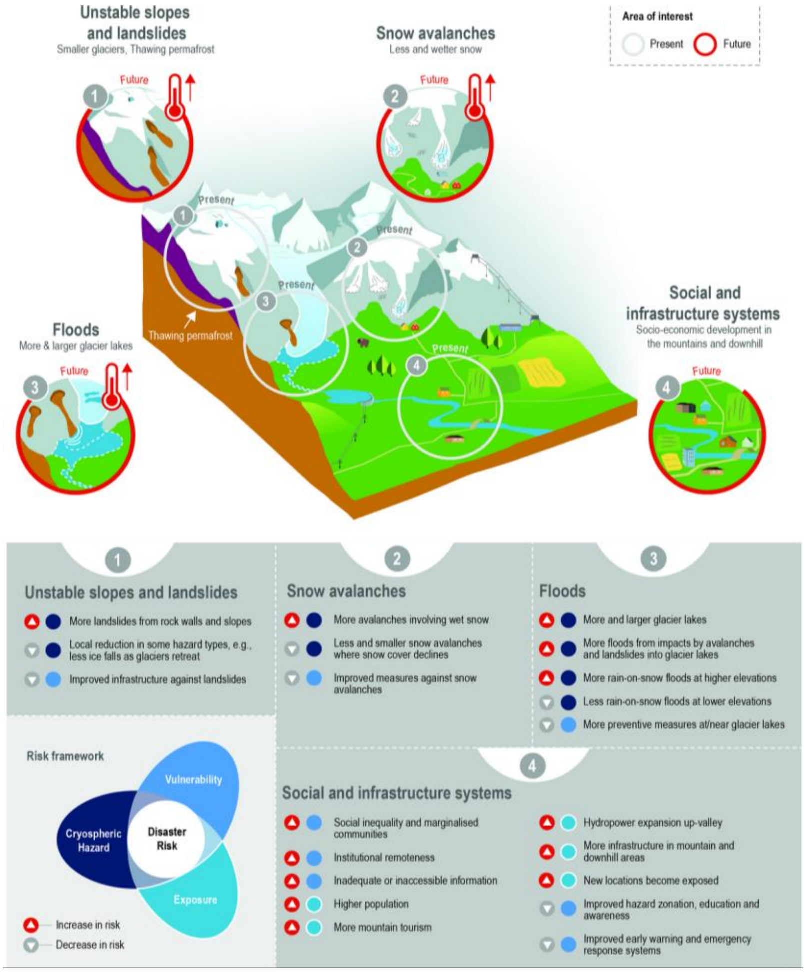

Figure 4.50: Anticipated changes in high mountain hazards (IPCC, 2022)

Climate Station S. Bernardino (SBE)

S. Bernardino is a small village located in the southern part of Switzerland, in the canton of Graubünden. It is situated in the Alps, at an altitude of around 1,680 meters above sea level, and has an alpine climate. The temperature models of the station show a temperature increase by 2-4°C by mid-century and 3-5°C by the end of the century. According to the IPCC in winter an increase in average runoff is to be expected due to more precipitation falling as rain under warmer condition. Summer runoff has been observed to decrease (IPCC, 2022). Summer heat waves have in recent years triggered rock instability with delays of only a few days or weeks in the European Alps (IPCC, 2022). Agriculture is also impacted by prolonged dry spells or heavy rain throughout the Alps. Increased competition between industries like hydropower, agriculture, and tourism is brought on by more droughts and less meltwater; low winter precipitation has already had an impact on the Italian Alps. To address rising demand, the IPCC report urges open, socially and environmentally responsible water management. Additionally, multi-use water management strategies are becoming more and more crucial. Mountain regions play a crucial role in the fight against the climate crisis, as they are a hotspot for biodiversity and provide us with ecosystem services. The government should invest in water infrastructure, such as dams, reservoirs, and water treatment plants, to improve water storage and distribution and control the higher runoff which is expected in winter. In summer, where leass runoff is expected, the government should promote water conservation measures, such as water-saving technologies and practices, to reduce water use and improve efficiency. Further, the government should establish protected areas, such as national parks, to conserve biodiversity in mountain areas. These areas can provide habitat for vulnerable species and ecosystems, and can also serve as a refuge for species that may be impacted by climate change. Additionally, the government can implement a range of conservation measures, such as habitat restoration and species reintroduction programs, to protect biodiversity in mountain areas. These measures can help to address specific threats to species and ecosystems, such as habitat loss and fragmentation. To address rock instability, the government can conduct geohazard assessments to identify areas that are at high risk. This can include using geological and geophysical surveys to identify potential hazards, as well as assessing the likelihood and potential impact of rockfall and landslides. Important is the implementation of early warning systems to alert communities and infrastructure managers of potential rock instability hazards. This can include using monitoring technologies, such as geosensors, to detect changes in rock conditions, as well as implementing communication systems to alert those at risk. Further, the government should conduct rock stabilization works to reduce the risk of rockfall and landslides. This can include installing rockfall barriers and catchment systems, as well as stabilizing unstable slopes using methods such as rock bolting, meshing, or retaining walls.

Climate Station Lugano (LUG)

Lugano is a city located in the southern part of Switzerland, in the Italian-speaking canton of Ticino. It is situated on the shore of Lake Lugano, surrounded by mountains, and has a subtropical climate. Kotlarski et al. (2023) project a strong warming for the summer season, for regions south of the main Alpine ridge, where Lugano is located. This statement is consistent with the temperature models generated for Lugano, which predict a warming of 3-4°C degrees by mid-century and 4-6°C by the end of the century. The minimum temperature in particular indicates consistent warming during the night periods. The rise in temperature is projected to increase the intensity, frequency and length of heatwaves, particularly in southern Switzerland. Higher average temperatures are expected to affect energy demand patterns, reducing energy needs for heating and increasing the demand for cooling (IEA, 2022). Coming to the impacts, first, as temperatures rise, Lugano is likely to experience more frequent and intense heatwaves, which can have a significant impact on human health, particularly among vulnerable populations such as the elderly and those with pre-existing health conditions. Second, with warmer temperatures, energy demand for cooling is expected to increase, while demand for heating may decrease. This could have implications for energy infrastructure and could increase the cost of cooling. Third, as temperatures rise, there may be changes in water availability, including reductions in stream flows and groundwater recharge. This could have implications for water management, particularly in areas where water resources are already stressed. Further, higher temperatures can have a significant impact on agricultural productivity and ecosystems, particularly in areas where water resources are limited. Changes in precipitation patterns and water availability could also affect the distribution of plant and animal species in the region. Last, as temperatures rise, the risk of forest fires may also increase, particularly in areas with dry and flammable vegetation. To mitigate these impacts the government should invest in renewable energy, improving energy efficiency, and promoting sustainable transportation. The government should develop and implement strategies to adapt to the impacts of climate change, such as improving water management and promoting drought-resistant crops. Moreover, the government can invest in infrastructure to improve energy efficiency and reduce greenhouse gas emissions. For example, the government could invest in public transportation, build green roofs and walls, and install energy-efficient heating and cooling systems in buildings.

In summary, the impacts of increasing temperatures in Switzerland will likely include melting of glaciers and snowpack, leading to changes in water availability for agriculture and drinking water, and increased risk of flash floods and landslides. Additionally, there may be changes in the distribution and abundance of plant and animal species, increased risk of heatwaves and associated health impacts, and changes in tourism and recreational opportunities. To use the SSP4.5 scenario for future climate change projections in Switzerland, it would be important to combine this scenario with more detailed information on how climate change will affect the specific geographic and climatic conditions in Switzerland. This can help to identify the most vulnerable regions and sectors and inform the development of adaptation strategies to reduce the risks associated with climate change. It is also important to consider the potential for future changes in social and economic factors, such as population growth and changes in land use, that can influence the extent of climate impacts and the effectiveness of adaptation measures.

4.5 Spatial Analysis Precipitation (QGIS)

In this chapter, we will look more specifically at the rain situation in SSP4.5. The reliability tests did not provide any significantly reliable results, so the precipitation situation in Switzerland will be examined in more detail here. The focus is placed on the closest two intervals, more precisely 2020 to 2040 (Figure 4.40) and 2040 to 2060 (Figure 4.41). To visually illustrate the rain situation rainfall maps were created with the application QGIS. To compare the two intervals with the observational data, a map was also created for the observational data. The rainfall maps show that the rainfall trends holistically will not change over the next years or decades according to scenario SSP4.5. The north-east remains the wettest area in Switzerland, which includes the station Säntis. This high amount of rainfall is due to the mountain's location and altitude, which causes moist air to rise and condense, resulting in heavy precipitation. Säntis is part of the eastern Swiss Alps and receives an average of 2,500 mm of precipitation per year. This can also be seen in Figure 4.39 below which shows the rainfall map of the observation data. In the future, according to generated Climate Model based on SSP4.5, the area may experience more extreme precipitation events, including heavier rainfall and more frequent and intense thunderstorms. This is expected due to the projected increase in global temperatures, which can cause more moisture to evaporate into the atmosphere and lead to more intense precipitation. The southern region of Switzerland experiences a Mediterranean climate with generally milder temperatures and drier conditions compared to other parts of Switzerland. The region is also characterized by a mountainous landscape, which can lead to significant variations in precipitation patterns depending on the location and altitude. The generated RCM expects the South to become slightly drier in the interval 2020-2040, while getting wetter again from 2040-2060. The reason for these changes could include more frequent and severe droughts, as well as more extreme precipitation events such as heavy rainfall and flash floods. Generally, the increase in global temperatures can lead to changes in precipitation patterns and weather extremes what makes it hard to predict the future. The Swiss Plateau, including the station Bern, receives around 800-1,000 mm of rainfall annually, with the highest amounts occurring in the summer months. Precipitation in the Swiss Plateau is influenced by the surrounding mountain ranges. The generated RCM suggests a slight decrease in rainfall in the interval 2020-2040 and a slight increase in the next interval 2040-2060. It is also to expect that this region will experience more frequent and severe droughts, as well as more extreme precipitation events such as heavy rainfall and flash floods.

Rainfall map Switzerland 2000-2020 (observation data)

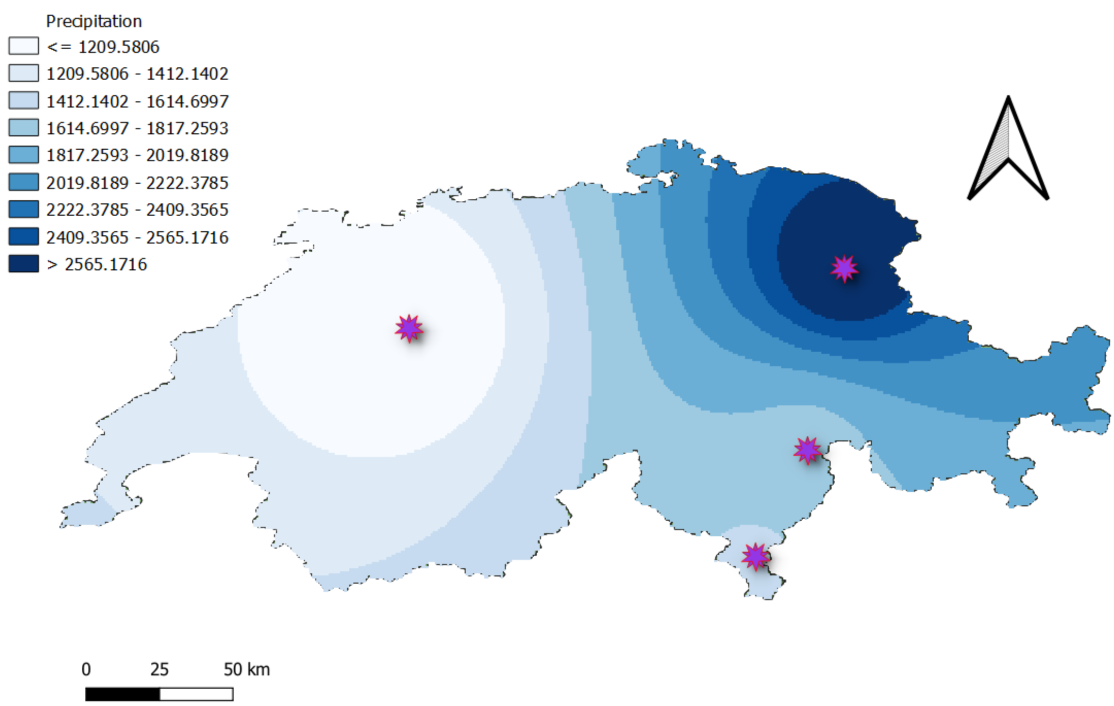

Figure 4.51: Spatial Analysis Average of Annual Precipitation, observation data 2000-2020

Rainfall map Switzerland 2020-2040 (SSP4.5)

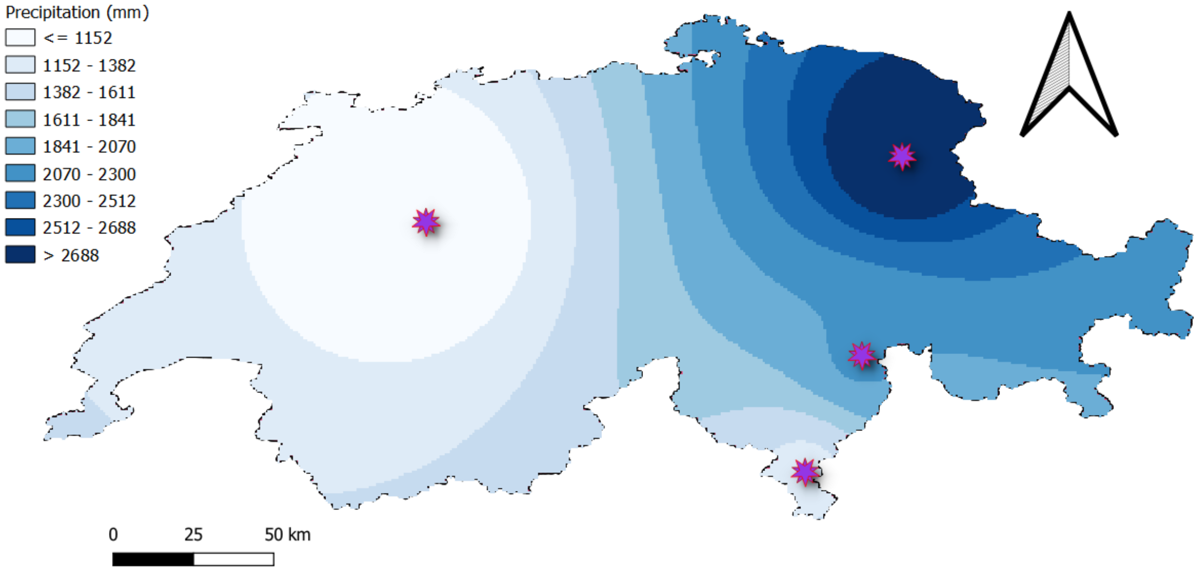

Figure 4.52: Spatial Analysis Average of Annual Precipitation, SSP4.5 2020-2040

Rainfall map Switzerland 2040-2060 (SSP4.5)

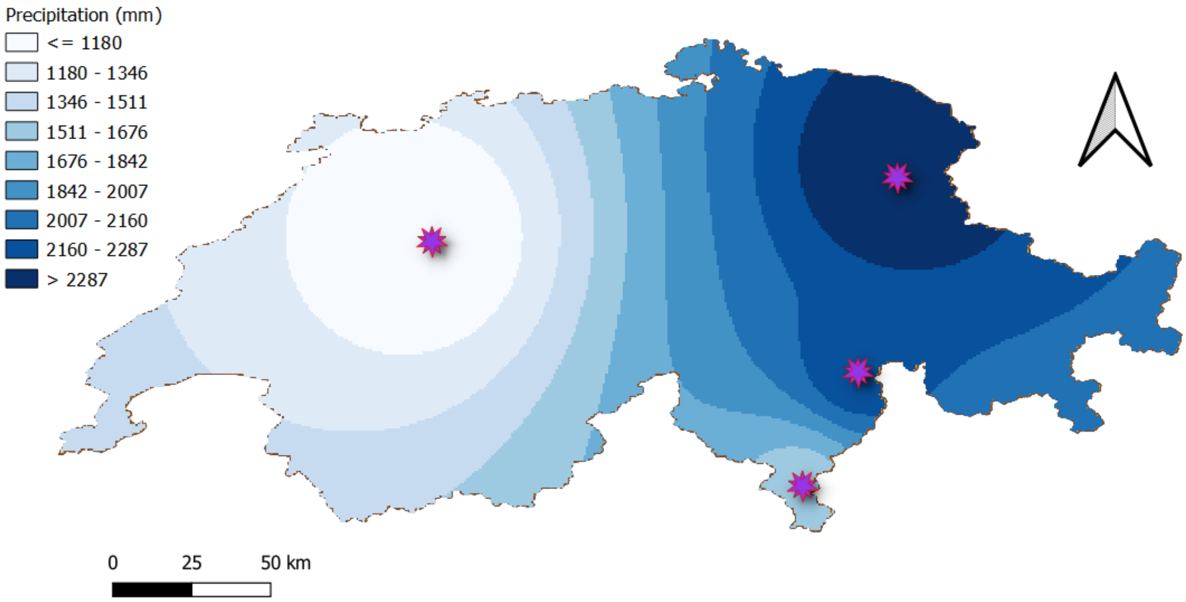

Figure 4.53: Spatial Analysis Average of Annual Precipitation, SSP4.5 2040-2060

CHAPTER 5

CONCLUSION

5.1 Conclusion

In conclusion, this proposed study developed a Regional Climate Model (RCM) for Switzerland based on precipitation and temperature (min/max) data using the Statistically Downscaling Method. The study examines the reliability of the RCM for Switzerland based on two scenarios - SSP4.5 and SSP8.5 - using various statistical tools such as Linear Regression, Cronbach's Alpha and Probability Density Function. Moreover, the study assessed the potential climate hazard based on the RCM created and recommend the most suitable SSP scenario for future climate change projection of Switzerland. SSP4.5 is seen as suitable scenario. The results of this study provide important insights into the potential impact of climate change on Switzerland and can support policymakers and stakeholders to take necessary steps to mitigate the climate hazards. The impacts of increasing temperatures in Switzerland will likely include melting of glaciers and snowpack, leading to changes in water availability for agriculture and drinking water, and increased risk of flash floods and landslides. Further, there will be an increased risk of heatwaves and associated health impacts, and changes in tourism and recreational opportunities. The proposed study contributes to the ongoing efforts to understand and address the complex challenges of climate change.

5.2 Limitation

The limitation of this proposed study is that the reliability test for precipitation did not show significant results in terms of reliability. Therefore, the rain models should be viewed with caution. In a next study, it could be considered to incorporate additional data sources or variables into the model to capture the complexity of precipitation patterns in Switzerland. This could include higher-resolution local data, as well as information on land use and other human activities that may impact precipitation. Finally, it may be helpful to acknowledge the inherent variability of precipitation patterns in the region and work to build a model that can capture this variability to the extent possible. The temperature models, on the other hand, have internal consistency and can be considered reliable.

In addition, it should be pointed out here that four stations are not sufficient to make reliable statements for Switzerland, which also includes the complex alpine region. It is recommended to include more stations in further studies.

CHAPTER 6

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ASSESSMENT OF POTENTIAL CLIMATE HAZARD IN SWITZERLAND USING LOCAL CLIMATE MODEL

APPENDIX

A thesis submitted to

Faculty of Engineering and Green Technology,

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in partial fulfillment of the requirements for the degree of

Master of Environmental Technology

April 2023

CHAPTER 7

APPENDIX

A METEO SWISS ORDER INVENTORY

Confirmation of the data ordered by the Federal Office of Meteorology and Climatology MeteoSwiss

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Federal Department of Home Affairs FDHA
Federal Office of Meteorology and Climatology MeteoSwiss

Data Inventory

Bern / Zollikofen	552	Precipitation; daily total 0 UTC - 0 UTC	rka150d0	mm	day	01.01.1991-31.12.2021
Bern / Zollikofen	552	Air temperature 2 m above ground; daily minimum	tre200dn	°C	day	01.01.1991-31.12.2021
Bern / Zollikofen	552	Air temperature 2 m above ground; daily maximum	tre200dx	°C	day	01.01.1991-31.12.2021
Lugano	273	Precipitation; daily total 0 UTC - 0 UTC	rka150d0	mm	day	01.01.1991-31.12.2021
Lugano	273	Air temperature 2 m above ground; daily minimum	tre200dn	°C	day	01.01.1991-31.12.2021
Lugano	273	Air temperature 2 m above ground; daily maximum	tre200dx	°C	day	01.01.1991-31.12.2021
Säntis	2501	Precipitation; daily total 0 UTC - 0 UTC	rka150d0	mm	day	01.01.1991-31.12.2021
Säntis	2501	Air temperature 2 m above ground; daily minimum	tre200dn	°C	day	01.01.1991-31.12.2021
Säntis	2501	Air temperature 2 m above ground; daily maximum	tre200dx	°C	day	01.01.1991-31.12.2021
S. Bernardino	1638	Air temperature 2 m above ground; daily minimum	tre200dn	°C	day	01.01.1991-31.12.2021
S. Bernardino	1638	Air temperature 2 m above ground; daily maximum	tre200dx	°C	day	01.01.1991-31.12.2021
S. Bernardino	1638	Precipitation; daily total 0 UTC - 0 UTC	rka150d0	mm	day	01.01.1991-31.12.2021

B PREDICTOR SCREENING

Correlation Analysis

P =Predictor	**BER Precip**	**BER T max**	**BER T min**	**SAE Precip**	**SAE T max**	**SAE T min**	**SBE Precip**	**SBE T max**	**SBE T min**	**LUG Precip**	**LUG T max**	**LUG T min**
P 1 - name	**mslp**	**p500**	**p500**	**p1_u**	**p500**	**p500**	**mslp**	**p500**	**p500**	**mslp**	**p500**	**p500**
P 1 - value	-0.319	0.783	0.7	0.534	0.879	0.869	-0.37	0.88	0.783	-0.338	0.746	0.729
P 2 - name	**p1_u**	**s850**	**s850**	**p5_f**	**s850**	**s850**	**p5_v**	**s850**	**s850**	**p1zh**	**s850**	**s850**
P 2 - value	0.303	0.818	0.912	0.368	0.798	0.813	0.476	0.78	0.884	-0.338	0.777	0.891
P 3 - name	**p8_u**	**shum**	**shum**	**p5_u**	**shum**	**shum**	**p8zh**	**shum**	**shum**	**p5_v**	**shum**	**shum**
P 3 - value	0.305	0.859	0.918	0.355	0.833	0.846	-0.399	0.833	0.9	0.432	0.823	0.908
P 4 - name	**p8zh**	**temp**	**temp**	**p8_f**	**temp**	**temp**	**prcp**	**temp**	**temp**	**p8zh**	**temp**	**temp**
P 4 - value	-0.304	0.938	0.94	0.338	0.869	0.878	0.501	0.91	0.933	-0.404	0.914	0.958
P 5 - name	**prcp**			**p8_u**						**prcp**		
P 5 - value	0.403			0.438						0.537		

Factor Analysis

P =Predictor	**BER Precip**	**BER T max**	**BER T min**	**SAE Precip**	**SAE T max**	**SAE T min**	**SBE Precip**	**SBE T max**	**SBE T min**	**LUG Precip**	**LUG T max**	**LUG T min**
P 1 - name	**p1zh**	**s500**	**s500**	**p1_u**	**s500**	**s500**	**p1zh**	**s500**	**s500**	**p1zh**	**s500**	**s500**
P 1 - value	~~-0.715~~	0.722	0.735	0.629	0.727	0.724	-0.721	0.719	0.731	~~-0.734~~	0.722	0.727
P 2 - name	**s500**	**s850**	**s850**	**p1_v**	**s850**	**s850**	**s500**	**s850**	**s850**	**s500**	**s850**	**s850**
P 2 - value	~~0.723~~	0.919	0.925	0.662	0.907	0.909	~~0.717~~	0.918	0.924	~~0.715~~	0.926	0.926
P 3 - name	**s850**	**shum**	**shum**	**p5_f**	**shum**	**shum**	**s850**	**shum**	**shum**	**s850**	**shum**	**shum**
P 3 - value	0.864	0.919	0.917	~~0.612~~	0.909	0.91	0.852	0.923	0.921	0.855	0.926	0.921
P 4 - name	**shum**	**temp**	**temp**	**p5_u**	**temp**	**temp**	**shum**	**temp**	**temp**	**shum**	**temp**	**temp**
P 4 - value	0.84	0.888	0.873	0.749	0.875	0.875	0.826	0.894	0.882	0.832	0.893	0.883
P 5 - name	**temp**						**temp**			**temp**		
P 5 - value	0.767						0.75			0.756		

C STEPS IN SDSM

Following the steps undertaken in SDSM to create the historical model as well as the models SSP4.5 and SSP8.5 are shown.

Legend file names

P = Precipitation

Tmax = Temperature maximum

Tmin = Temperature minimum

obs = Observation data (data from the Swiss Federal Office of Meteorology and Climatology)

h = Historical model, generated from historical predictors

sum = Summary file

Calibration file

Input file: Observation file

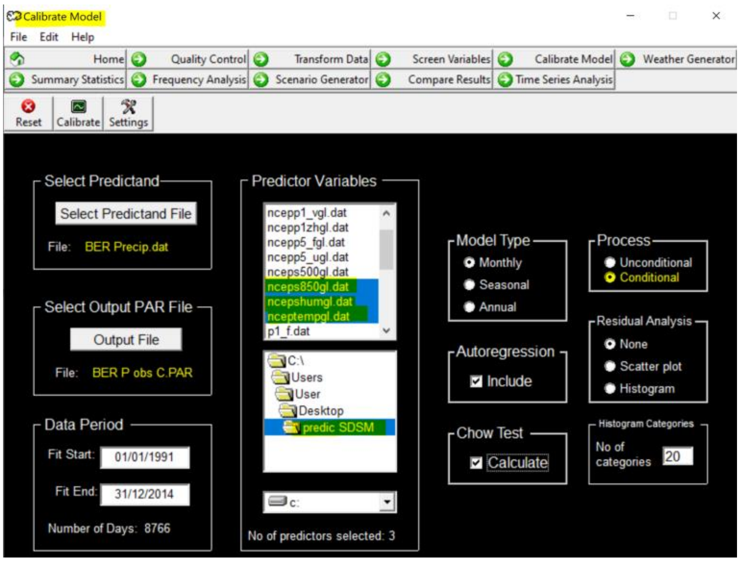
Predictor Variables

File used: NCEP-DOE_1979-2014.

Predictor variables from the National Centre for Environmental Prediction. Since the study period begins in 1991, the data from 1991 - 2014 were included. The data was included in the downloaded CMIP6 data for the location Switzerland (grid cell box: Box_4X_49Y). The predictors (3-4 per dataset) were determined in advance by the predictor screening in SPSS.

Output file: Calibration file

For Precipitation data the Process “Conditional” is selected, because Rainfall data can not be negative. Meaning, either there was rainfall on the specific day what is shown in a positive value or there was no rain what is shown with the value “0”. On the other side, Temperature data (max/min) can be negative, therefore for these datasets “Unconditional” is selected.



Scenario Generation

Input file: Calibration file

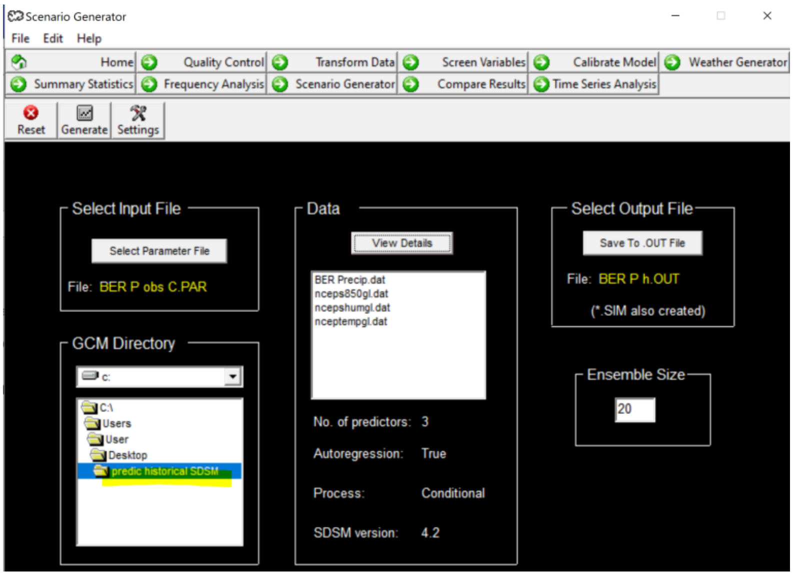
GCM Directory

Predictors for historical model: CanESM5_historical_1979-2014

Predictors for scenario 4.5: CanESM5_ssp245_2015-2100

Predictors for scenario 8.5 CanESM5_ssp585_2015-2100

Output file: Scenario file



Historical Model: Summary Statistics

To compare the observation file with the historical model file, both are summarized.

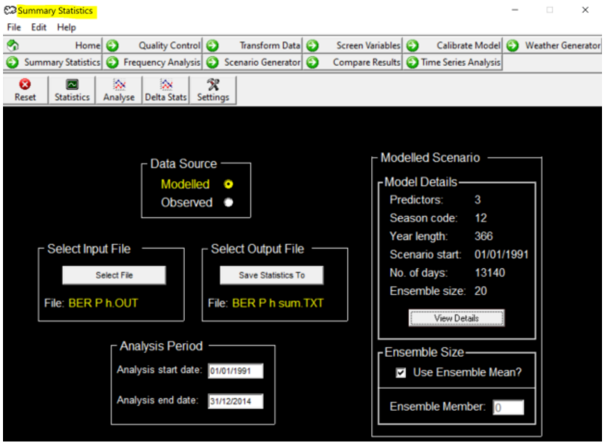
Data Source

Observation file: Data source "Observed"

Scenario file: Data source "Modelled"

Input file: observation file resp. historical model file

Output file: summary of observation file resp. historical model file

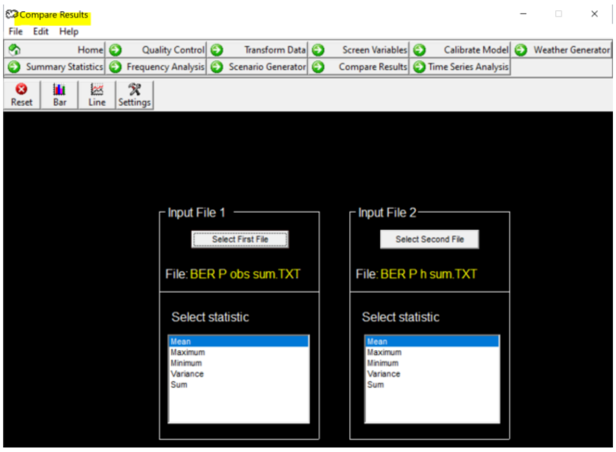


Historical Model: Comparison Observation Data

The two generated summary files are uploaded and "Mean" selected to compare them. The buttom "Line" is pressed to start the analysis and receive a line chart as output.

Input File 1: Summary observation file

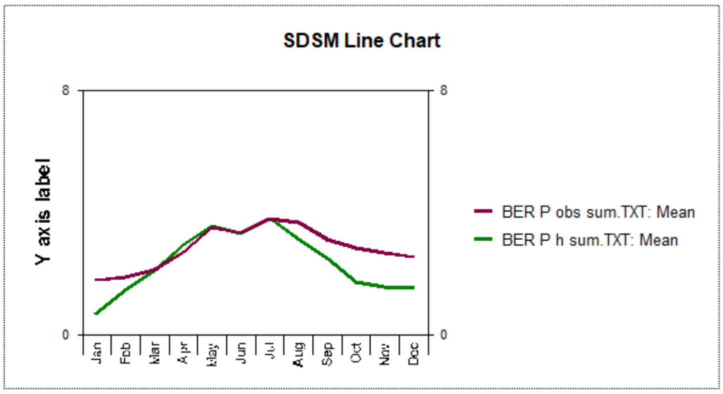
Input File 2: Summary historical model file

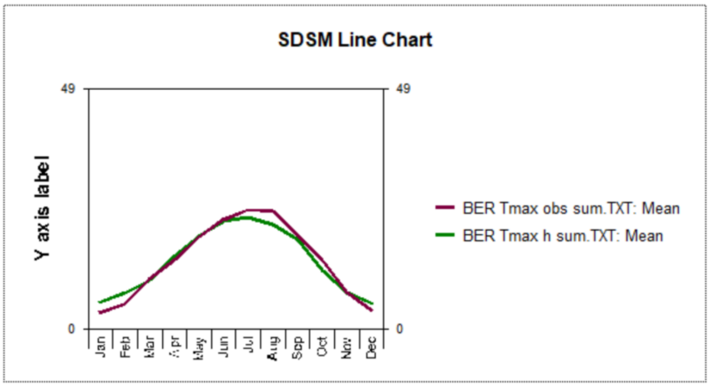


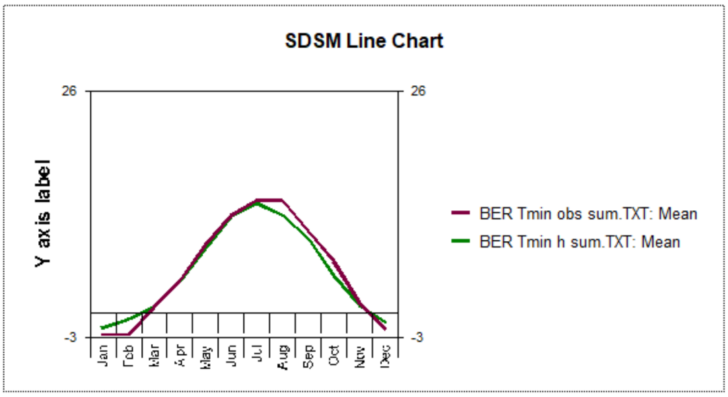
D RESULTS HISTORICAL MODEL

Following the historical models, created in SDSM, are shown. The charts show the comparison between observation data and historical model for the four climate stations. Each in the order: Precipitation, Temperature max, Temperature min.

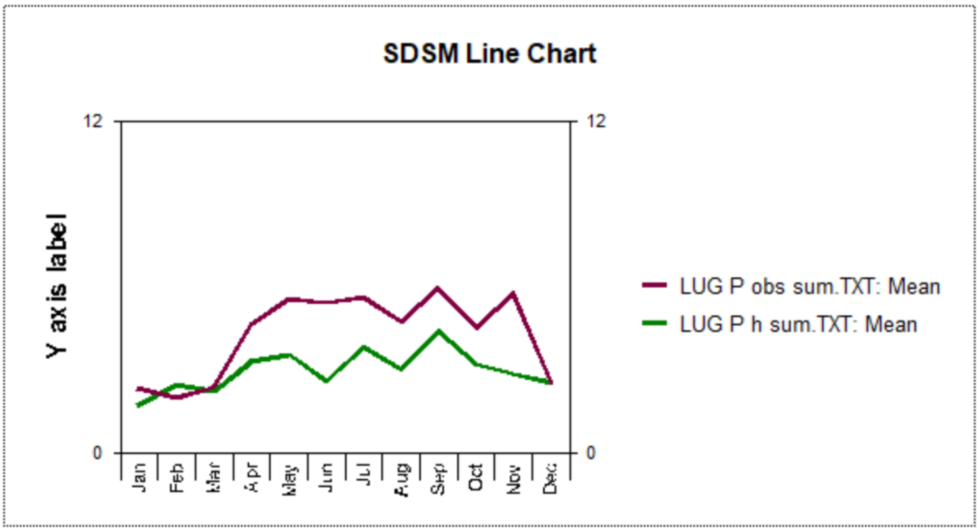
Historical Model Station BER

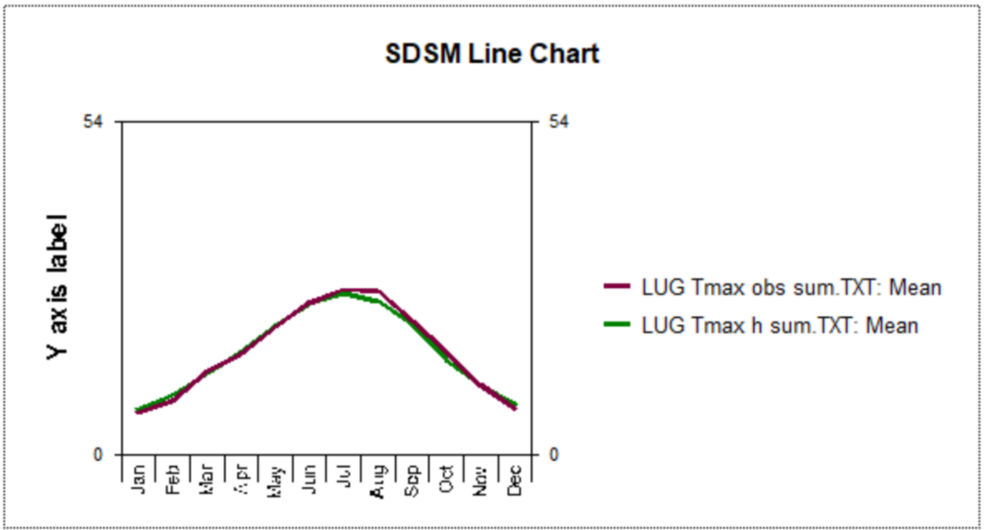


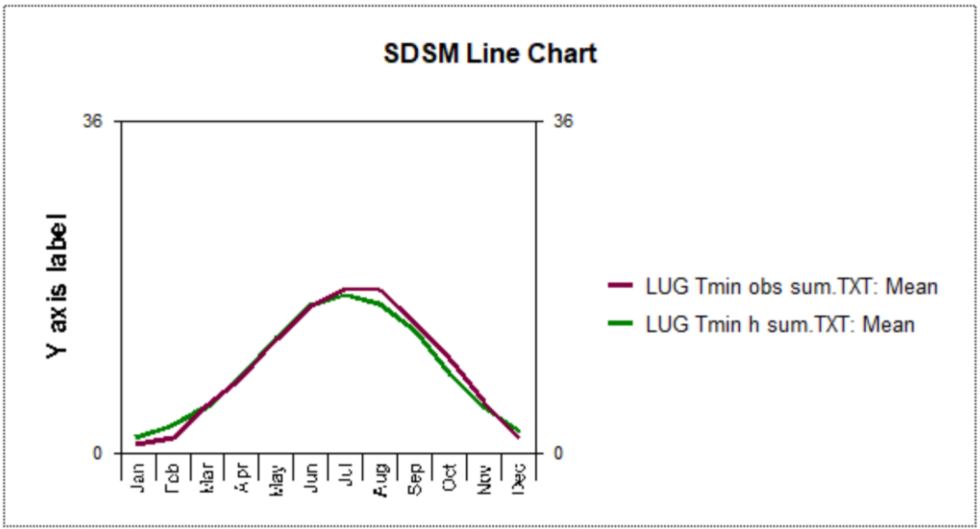




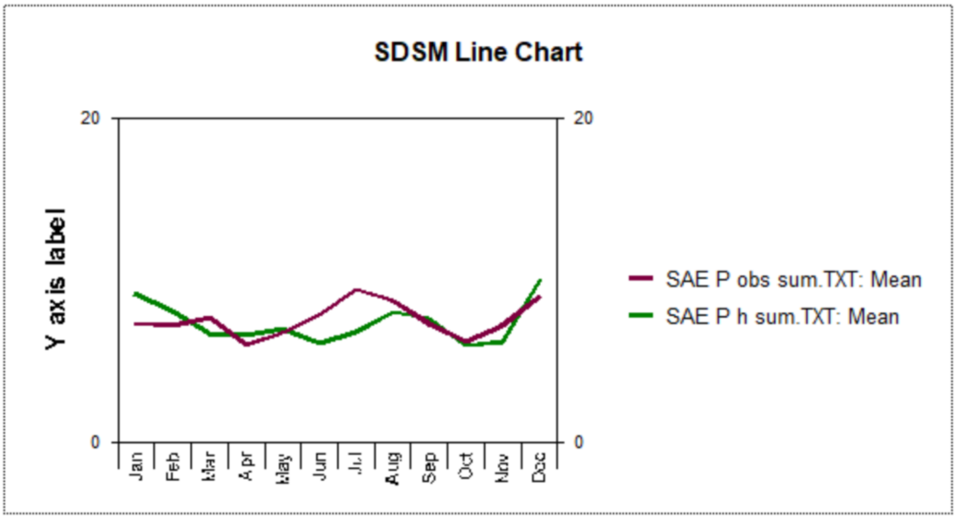
Historical Model Station LUG

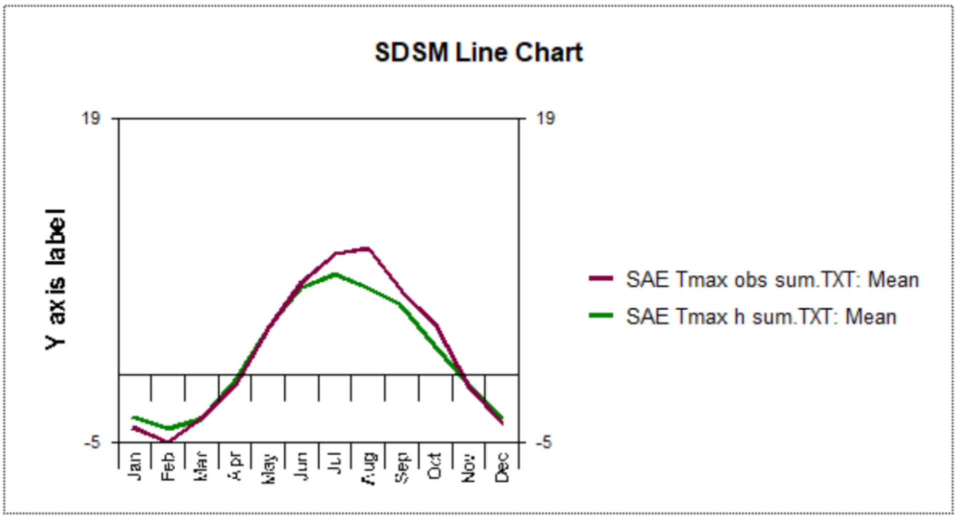


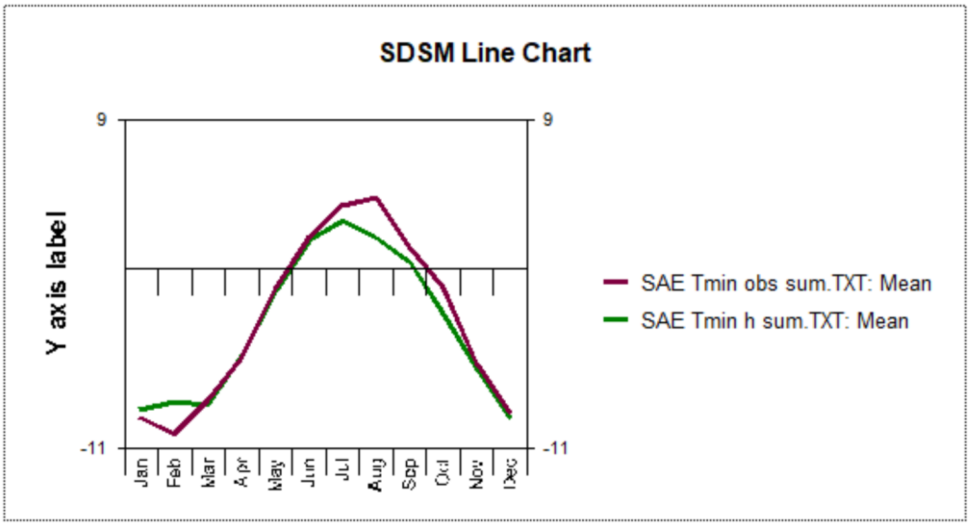




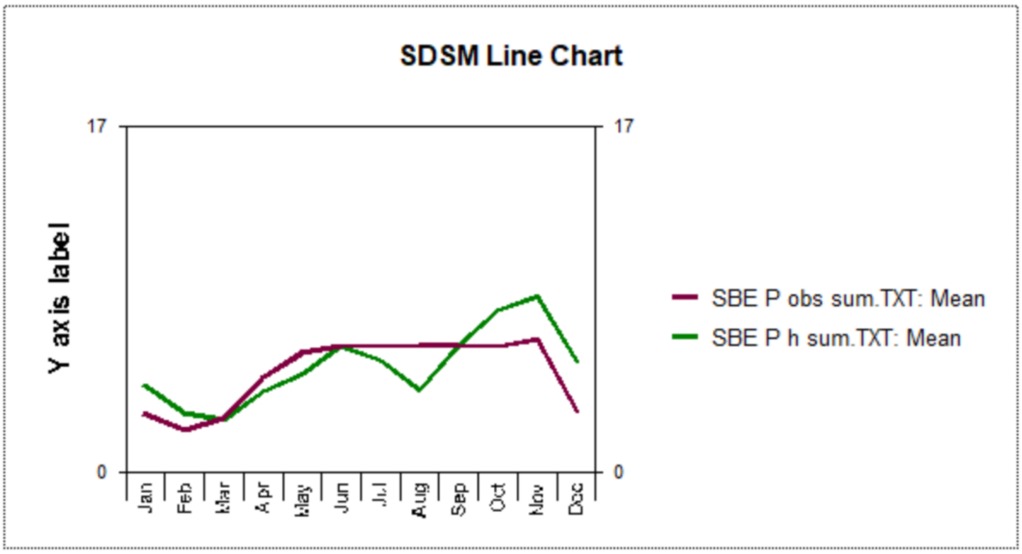
Historical Model Station SAE

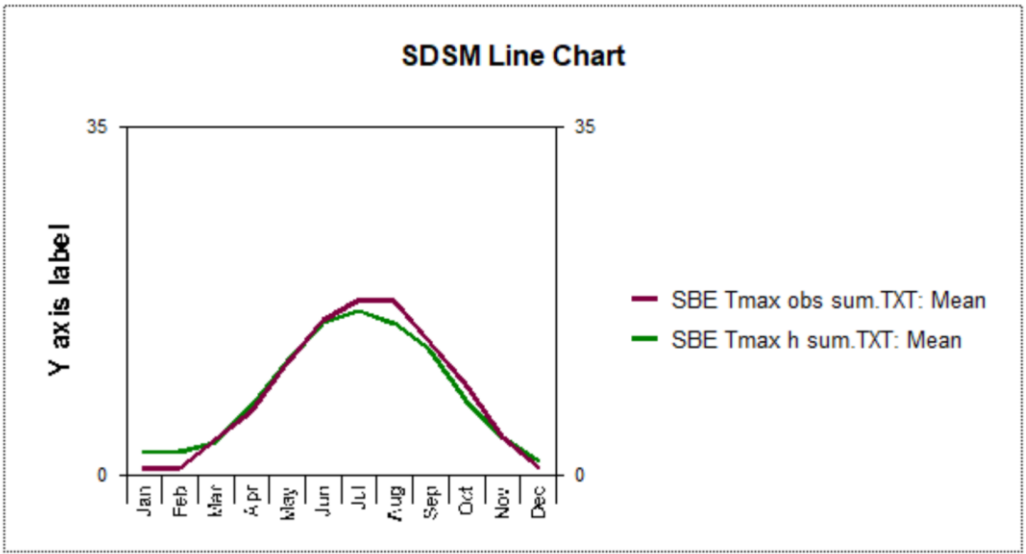


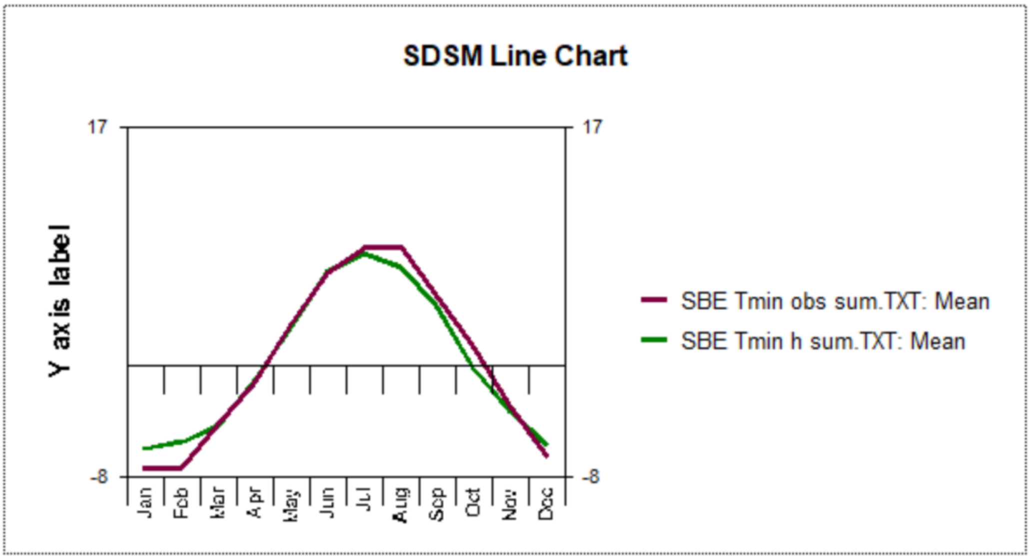




Historical Model Station SBE

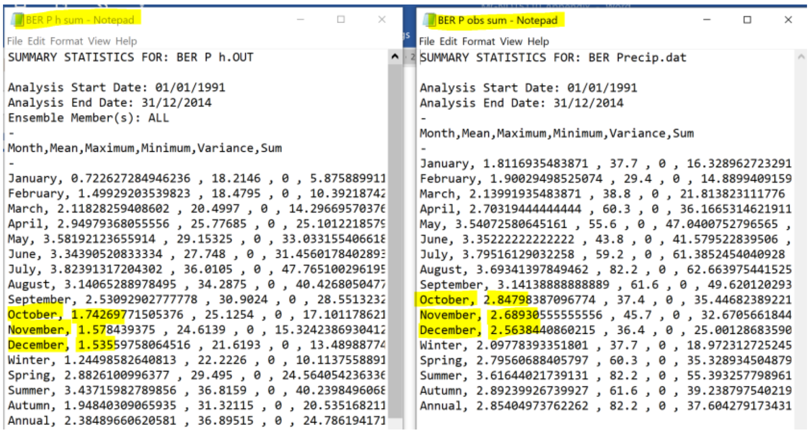






E BIAS CORRECTION

The historical models show the comparison between the observation data and the generated historical model data. If the two curves match, it can be assumed that the data are correct and therefore the calculated models SSP 4.5 and SSP 8.5 are also correct. The historical models concerning the temperatures (max and min) show a good agreement and therefore do not require a bias correction. This is not the case for precipitation, where the lines show deviations for specific months. Therefore, a bias correction is performed for the precipitation models SSP 4.5 and SSP 8.5. The text files of the two data sets are opened to calculate the difference. This difference is then added to or subtracted from the monthly data of the models. The unit of measurement of the data is millimeter mm. If the observation data shows more rainfall, and therefore this curve is above the curve of the historical model, the difference is added. If the observation data show less rainfall or the curve of the observation data is below that of the historical model, the difference is subtracted. As an example, the model of station BER is shown below. the two text files (historical model and observation data) are opened and the difference is calculated.



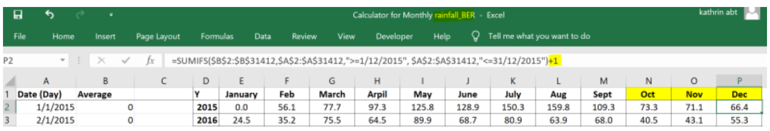
BER P h sum - Notepad

```
SUMMARY STATISTICS FOR: BER P h.OUT

Analysis Start Date: 01/01/1991
Analysis End Date: 31/12/2014
Ensemble Member(s): ALL
-
Month,Mean,Maximum,Minimum,Variance,Sum
-
January, 0.722627284946236 , 18.2146 , 0 , 5.875889911
February, 1.49929203539823 , 18.4795 , 0 , 10.39218742
March, 2.11828259408602 , 20.4997 , 0 , 14.2966957037
April, 2.94979368055556 , 25.77685 , 0 , 25.101221857
May, 3.58192123655914 , 29.15325 , 0 , 33.033155406618
June, 3.34390520833334 , 27.748 , 0 , 31.456017840289
July, 3.82391317204302 , 36.0105 , 0 , 47.765100296195
August, 3.14065288978495 , 34.2875 , 0 , 40.426805047
September, 2.53092902777778 , 30.9024 , 0 , 28.5513232
October, 1.74269771505376 , 25.1254 , 0 , 17.101178621
November, 1.578439375 , 24.6139 , 0 , 15.324238693041
December, 1.53559758064516 , 21.6193 , 0 , 13.48988774
Winter, 1.24498582640813 , 22.2226 , 0 , 10.1137558891
Spring, 2.8826100996377 , 29.495 , 0 , 24.564054236336
Summer, 3.43715982789856 , 36.8159 , 0 , 40.239849606
Autumn, 1.94840309065935 , 31.32115 , 0 , 20.535168211
Annual, 2.38489660620581 , 36.89515 , 0 , 24.786194171
```

BER P obs sum - Notepad

```
SUMMARY STATISTICS FOR: BER Precip.dat

Analysis Start Date: 01/01/1991
Analysis End Date: 31/12/2014
-
Month,Mean,Maximum,Minimum,Variance,Sum
-
January, 1.8116935483871 , 37.7 , 0 , 16.328962723291
February, 1.90029498525074 , 29.4 , 0 , 14.8899409159
March, 2.13991935483871 , 38.8 , 0 , 21.813823111776
April, 2.70319444444444 , 60.3 , 0 , 36.1665314621911
May, 3.54072580645161 , 55.6 , 0 , 47.0400752796565 ,
June, 3.35222222222222 , 43.8 , 0 , 41.579522839506 ,
July, 3.79516129032258 , 59.2 , 0 , 61.385245404092
August, 3.69341397849462 , 82.2 , 0 , 62.663975441525
September, 3.14138888888889 , 61.6 , 0 , 49.620120293
October, 2.84798387096774 , 37.4 , 0 , 35.44682389221
November, 2.68930555555556 , 45.7 , 0 , 32.6705661844
December, 2.56384440860215 , 36.4 , 0 , 25.00128683590
Winter, 2.09778393351801 , 37.7 , 0 , 18.972312725245
Spring, 2.79560688405797 , 60.3 , 0 , 35.328934504879
Summer, 3.61644021739131 , 82.2 , 0 , 55.393257798961
Autumn, 2.89239926739927 , 61.6 , 0 , 39.238797540219
Annual, 2.85404973762262 , 82.2 , 0 , 37.604279173431
```

This is then added to the excel document in which the monthly values are calculated.



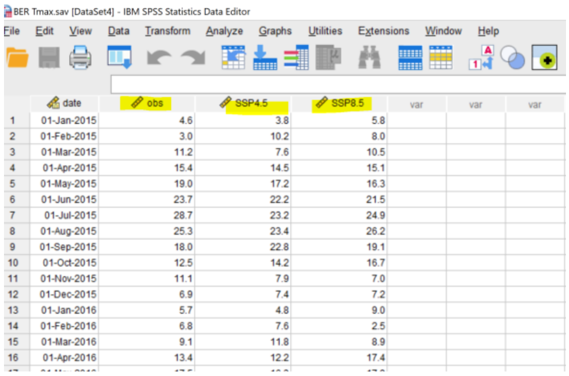
Calculator for Monthly rainfall_BER - Excel

P2 =SUMIFS($B$2:$B$31412,$A$2:$A$31412,">=1/12/2015", $A$2:$A$31412,"<=31/12/2015")+1

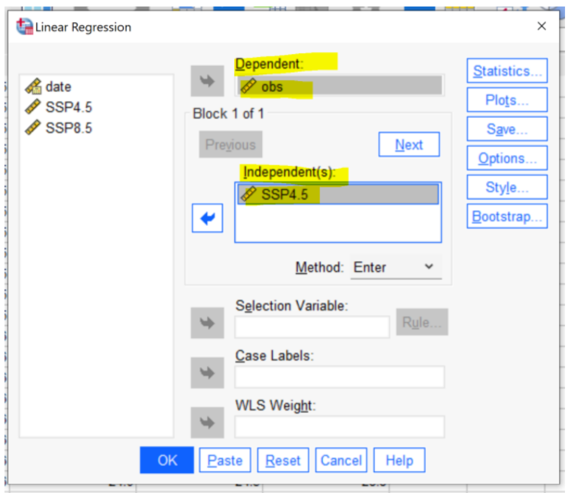
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Date (Day)	Average		Y	January	Feb	March	Arpil	May	June	July	Aug	Sept	Oct	Nov	Dec
2	1/1/2015	0		2015	0.0	56.1	77.7	97.3	125.8	128.9	150.3	159.8	109.3	73.3	71.1	66.4
3	2/1/2015	0		2016	24.5	35.2	75.5	64.5	89.9	68.7	80.9	63.9	68.0	40.5	43.1	55.3

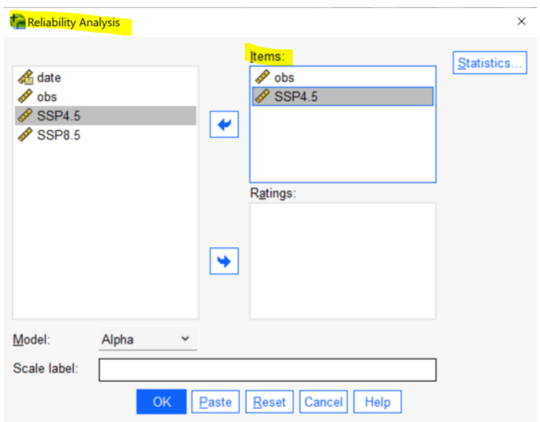
F LINEAR REGRESSION AND CRONBACH'S ALPHA

For the calculation, the observation data, and the data from SSP4.5 and SSP8.5 are listed side by side. The data are the monthly values of the years 2015 to 2021. The first figure shows the imported data. The second and third photos show the Linear Regression and Cronbach's Alpha function in SPSS.



	date	obs	SSP4.5	SSP8.5
1	01-Jan-2015	4.6	3.8	5.8
2	01-Feb-2015	3.0	10.2	8.0
3	01-Mar-2015	11.2	7.6	10.5
4	01-Apr-2015	15.4	14.5	15.1
5	01-May-2015	19.0	17.2	16.3
6	01-Jun-2015	23.7	22.2	21.5
7	01-Jul-2015	28.7	23.2	24.9
8	01-Aug-2015	25.3	23.4	26.2
9	01-Sep-2015	18.0	22.8	19.1
10	01-Oct-2015	12.5	14.2	16.7
11	01-Nov-2015	11.1	7.9	7.0
12	01-Dec-2015	6.9	7.4	7.2
13	01-Jan-2016	5.7	4.8	9.0
14	01-Feb-2016	6.8	7.6	2.5
15	01-Mar-2016	9.1	11.8	8.9
16	01-Apr-2016	13.4	12.2	17.4





G PROBABILITY DENSITY FUNCTION

Since the observation data (raw data) are to be compared with the two developed models (SSP4.5 and SSP8.5), three data sets are used. The datasets are copied into Excel. Then below the data the average and estimates standard deviation based on a sample will be calculated with the formulas AVERAGE and STDEV. Then the z-score is calculated using the formula: $Z = (x - \mu) / \sigma$. It is a useful tool for analyzing the standard deviation of a data set and comparing individual values to the overall distribution. The z-score is a standardized score that indicates how many standard deviations a particular value is from the mean. Subsequently the NORM.DIST function is used to calculate the PDF. The NORM.DIST function calculates the probability of a given value occurring in a normal distribution. The figure below shows that the z-score and the PDF were calculated for each data set. After the PDF has been calculated, the graphs can be created and interpreted.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Observation	PDF (OBS)	Z score (OBS)			SSP 4.5	PDF (Model)	Z score			SSP 8.5	PDF (Model)	Z score	
2	0.8	0.1	-1.8	80.2		0.0	0.1	-1.7	82.4		0.0	0.0	-2.2	81.25
3	18.1	0.2	-1.4	45.3		12.6	0.1	-1.5	47.4		21.9	0.1	-1.6	36.77951
4	21.2	0.2	-1.3			20.6	0.2	-1.3			23.0	0.1	-1.6	
5	22.8	0.2	-1.3			21.6	0.2	-1.3			27.5	0.1	-1.5	
6	23.9	0.2	-1.2			23.2	0.2	-1.2			30.7	0.2	-1.4	
7	24.2	0.2	-1.2			24.5	0.2	-1.2			30.8	0.2	-1.4	
8	26.9	0.2	-1.2			29.2	0.2	-1.1			36.4	0.2	-1.2	
9	31.1	0.2	-1.1			29.7	0.2	-1.1			39.8	0.2	-1.1	
10	32.5	0.2	-1.1			31.9	0.2	-1.1			39.8	0.2	-1.1	
11	34.3	0.2	-1.0			33.7	0.2	-1.0			41.4	0.2	-1.1	
12	35.7	0.2	-1.0			35.2	0.2	-1.0			43.0	0.2	-1.0	
13	35.8	0.2	-1.0			35.9	0.2	-1.0			44.0	0.2	-1.0	
14	38.9	0.3	-0.9			37.4	0.3	-0.9			44.2	0.2	-1.0	
15	40.4	0.3	-0.9			39.2	0.3	-0.9			45.9	0.3	-1.0	