Universität für Bodenkultur Wien

University of Natural Resources and Life Sciences, Vienna

Department of Water, Atmosphere and Environment

Institute of Hydrology and Water Management (HyWa)

ASSESSMENT AND COMPARISON OF METEOROLOGICAL (RE-)ANALYSIS DATA FOR HYDROLOGICAL MODELLING IN ALPINE REGIONS

Master thesis

In partial fulfilment of the requirements

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Diplom-Ingenieurin

submitted by:

STEINMAYR, KATHARINA JOHANNA

Supervisor: Hubert Holzmann, Ao.Univ.Prof. Dipl.-Ing. Dr.nat.techn.

Co-Supervisor: Mathew Herrnegger, Dipl.-Ing. Dr.nat.techn.

Student Number 01340840

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Am Ende sind noch alle Personen zu nennen, die mich oder meine Masterarbeit in sonstiger Weise unterstützt haben.

Abstract

Satisfactory input data are the main driving forces for the correctness of a hydrological model, which is for example used in rainfall-runoff model forecasting. It is important to gain insights on the quality of the input data, as this variable can highly influence the output of the model.

The aim of this thesis is to critically investigate four different data sets (SPARTACUS, INCA, COSMO-REA6 and E-OBS) as potential input data for hydrological models. Based on gridded data sets, daily precipitation and temperature data are assessed and compared for the period 2003 and 2015. As a study area two catchments in Austria are chosen: Salzach and Ybbs, which are subdivided. On these subcatchments, it is analysed, whether the data sets have a higher agreement for larger than for smaller catchment areas, and whether the bias between the data sets are less significant when a small range of elevation is characterizing the catchment. Statistic parameters are calculated to show differences in the data. Diagrams together with maps graphically demonstrate variation and consistency in the meteorological data. Regularities and bias between the data sets are outlined.

The results show that regularities of the data are difficult to find as the data sets and the bias show a significant scatter. E-OBS, a data set that is interpolation-based, has the highest bias and the author of this thesis recommends not to use this data set for hydrologic modelling. As SPARTACUS and INCA have the highest spatial resolution and Austria shows a complex topography and different small-scale processes, those data sets are likely to represent the local patterns best. The large spatial coverage of COSMO-REA6 can be of high importance for projects with a Europe-wide study area and therefore further focus should be put on COSMO-REA6 as well.

Kurzfassung

Hydrologische Modelle, die beispielsweise in Abflussberechnungen verwendet werden, benötigen Eingangsdaten von hoher Qualität, um eine Richtigkeit des Modells zu garantieren. Es ist wichtig zu wissen, wie sich die Daten verhalten, denn das Modellergebnis wird durch die Beschaffenheit der Eingangsdaten sehr stark beeinflusst.

Das Ziel dieser Masterarbeit ist es, vier verschiedene Datensätze (SPARTACUS, INCA, COSMO-REA6 und E-OBS) als mögliche Eingangsdaten für hydrologische Modelle zu untersuchen. Dabei werden Rasterdatensätze mit täglichen Niederschlags- und Temperaturwerten zwischen den Jahren 2003 und 2015 miteinander verglichen. Als Untersuchungsgebiet sind die österreichischen Einzugsgebiete Salzach und Ybbs ausgewählt worden, die in kleinere Flächen unterteilt worden sind. In diesen Teileinzugsgebieten wird untersucht, ob die Datensätze in größeren Einzugsgebieten eine bessere Übereinstimmung aufweisen als in kleinen, beziehungsweise ob die Höhe eines Gebiets Einfluss auf die Abweichungen nimmt. Statistische Parameter werden berechnet, um Unterschiede in den Daten anzuzeigen. Darüber hinaus werden an Hand von unterschiedlichen Diagrammen und Karten die Ähnlichkeiten und die Differenzen der Datensätze ausgearbeitet.

Die Ergebnisse zeigen, dass systematische Abweichungen und Regelmäßigkeiten in den Unterschieden der Datensätze schwer zu finden sind, da Streuungen und Schwankungen erkennbar sind. E-OBS, ein Datensatz der nur durch Interpolation von wenigen Messwerten berechnet wird, hat die stärksten Abweichungen. Daher wird davon abgeraten, diesen für eine hydrologische Modellierung in Österreich zu verwenden. SPARTACUS und INCA weisen die höchste räumliche Auflösung auf, weshalb sie kleinräumige, lokale Prozesse besser widerspiegeln können. COSMO-REA6 berechnet die meteorologischen Datensätze für ganz Europa. Dies ist vor allem für länderübergreifende Projekte von hoher Bedeutung, weshalb dieser Datensatz noch für weitere Untersuchungen herangezogen werden sollte.

Abbreviations

AT	Austria
DE	Germany
DJF	December, January, February
IQR	Interquartile Range
JJA	June, July, August
km	Kilometer
MAM	March, April, May
masl	meters above sea level
mm	Millimeters
NWP	numerical weather prediction
SON	September, October, November
ZAMG	Central Institution for Meteorology and Geodynamics
°C	degree Celsius

Contents

1. Introduction

This chapter introduces the reader to the topic of hydrological models and gives background information for a better understanding of the issue covered in this master thesis.

1.1 Application in hydrological models

Hydrological models are used for different purposes, one of them being precipitation-runoff forecasting. Satisfactory input data, especially precipitation, are the main driving forces for the correctness of the models. No matter how well the determining physical processes are described in a rainfall-runoff model, the quality of the input precipitation data will highly influence the output of the model. Density and location of observation stations play a key role for the quality of the input data. Due to for example geographic and economic reasons the number of observation stations are limited, and fewer and poorly located stations lead to worse results in hydrological models as shown in various papers (Xu et al. 2013).

Over the past two decades, gridded (reanalyses) data are more and more used as input data to hydrological models. Gridded data generally mean, that observation data from different sources are combined with interpolation and assimilation techniques to create a data set on a continuous spatial and temporal resolution. Most commonly, gridded data sets are either reanalysis or remote sensing data, or interpolation from stations observations. Reanalyses data describe that the data are calculated with a numerical weather prediction model (NWP). The model is constrained by observations, collected from different sources as shown in Table 1-1. This table summarizes the characteristics of various precipitation data sets. Interpolation data means, that data is estimated between scattered point measurements. These measurements are mostly provided by observation stations and they show a spatio-temporal variability. Different techniques make a calculation of the relation between known and unknown points or cells possible and some of them – used in the researched data sets – are outlined in chapter 2.

When working with gridded data, it is important to keep in mind which observations are used in the model, as systematic biases can appear. Although gridded data sets vary in space and time, it can be said that the results are more accurate with a denser network of observation stations. A higher level of observations equals a higher level of boundary conditions. Consequently, with more observations available, the model is higher constraint, whereas with less observations the model follows its own built-in variability. Reanalysis data are also used for short-time forecasts (Raimonet et al. 2017; Schulz 2018; Solaiman and Simonovic 2011; Sitterson et al. 2017).

Table 1-1: Summary of observed precipitation data set characteristics (Sitterson et al. 2017)

Observed	Method	Spatial Extent	Spatial Resolution	Temporal Resolution	Years of data	Precipitation Output	Error
Rain Gauge	Physically collected on the ground	Specific locations	Lat.-Lon. of station, 0.009x0.009 or 0.5x0.5-degree grid interpolation	Hourly, Daily, Monthly, Yearly	100 years	Underestimates heavy rainfall events	Random error, mechanical issues, location
Radar	Technologically collected on the ground	Radial area around station (radius 230km)	1x1 degree grid, lat. and long of station	Hourly, 3-hourly,	30-40 years	Overestimates heavy rainfall events, underestimates light rainfall	Signal blockage, hail misreading
Satellite	Technologically collected from space	Latitude range (60°N, 60°S)	0.04x0.04-degree grid 0.1x0.1-degree grid 0.25x0.25-degree grid	Half-Hourly, Hourly, Daily	20 years or less	Underestimates rain from warm top clouds	Frozen precipitation, multilayer clouds

On a positive note, gridded data are nowadays easy to access, and they provide a spatial and temporal homogeneity and they have constant time steps and a steady grid. The problem with gridded data is, that the integrated system is difficult to understand and not a lot of information about the quality of the input observation data are provided. It is for example uncertain to which extent the integrated systems of the gridded data sets use the observation data and work around missing data (Raimonet et al. 2017).

There are many different data sets and the challenge is to use the right one for the research problem or the hydrological model. As the data sets have different resolutions and extents, these are often the determining factors. The spatial and temporal resolution that a gridded data set is expected to have, is primarily depending on the hydrological problem. A higher resolution with more observation is provided by a regional data set which is of importance for regional hydrological models. They provide more details in finer dimensions and are therefore better for a regional model, than a global data set, as a better understanding of small-scale processes in the regional data set can be assumed.

Global products might use calibration balanced on the errors to make biases small, leading to models which are not as sensitive as regional products. According to the extent of the hydrological problem, the data set must be chosen (Essou, Brissette, and Lucas-Picher 2017).

Another aspect for deciding on a data set is the time that the data set covers. Hydrological models often require long-term time series of meteorological data. For these series however, it is important that the observation data used for assimilation in the reanalysis data, show homogeneity. The homogeneity of reanalysis data defines to which extent the data set can be used (Raimonet et al. 2017).

Evaluating and inter-comparing the meteorological data sets is crucial before using them in a hydrological model. Especially in mountainous regions, hydrologic modelling is challenging as observations cannot cover whole regions. To evaluate meteorological data sets, different approaches are available: Comparisons can be conducted with observation data, gridded data sets, observation-only-based gridded data sets or – a quite rarely used approach – by comparing the output of hydrological models to gain insight on the input data. Raimonet et al. (2017) list the accounting for topography and temperature gradients with altitude as two of the most important parameters for improving the meteorological data as input data for the hydrological model. A high spatial resolution is needed to get better representation of the topography, as the differences in height can be displayed better with a denser grid net. Raimonet et al. (2017) get to the conclusion, that a high-resolution topography and the elevation gradient are especially important in mountainous regions to get good results for temperature and precipitation. However, they also state in their paper, that better results are achieved for catchments with a larger area, due to their averaging effect. Moreover, it is explained that for small catchments a high resolution is not automatically connected to a high spatial heterogeneity. This is greatly linked to a dense observation network and that the physical model for the reanalysis data can display small-scale processes. A dense observation network allows a detailed description of meteorological data which has a high importance to hydrological models, as the phases of precipitation are significant for streamflow simulations (Raimonet et al. 2017).

1.2 Clim2Power

People all over the world are concerned about climate change. Each sector tries to find different solutions on how to face the challenges of climate change, which is largely driven by electricity demand and energy production by fossil fuels. Finding and planning alternative strategies for energy production is therefore one of the biggest questions in the 21st century. On top of it, electricity demand will highly be affected by global warming, calling for strong mitigation policies and strategies. A promising way contributing to this issue is to increase renewable energy production, for example hydroelectricity. Generating power using water, however, is largely influenced by weather conditions. In order to plan and effectively use hydropower, long-time forecasts of regional weather patterns are needed. They determine the volume of the water, which the produced electricity is depending on (Intergovernmental Panel on Climate Change 2014).

This master thesis is related to the project “Clim2Power: Translating climate data into power plants operational guidance”. Clim2Power is an EU wide research project between Portugal, Sweden, Ireland, Germany, Austria and France that works on an easily accessible Climate Service. Figure 1-1 shows the planned workflow of Clim2Power. The research focuses on how hydro, wind and solar power operation are influenced by the climate. Furthermore, emphasis is put on electricity demand and the power system in general. The goal is to make complex scientific model-based knowledge accessible for the end user, by creating a web service that unites climate data, hydrological models, renewable energy resources, power simulation tools, energy system and electricity models. Based on this information a forecast for the next six months can be created, that shows power system shifts due to a shortage or surplus in wind and hydroelectricity. Clim2Power is an approach to face the challenges provided in using renewable energy systems, which differ interseasonally (“Clim2Power” 2018; Holzmann 2017).

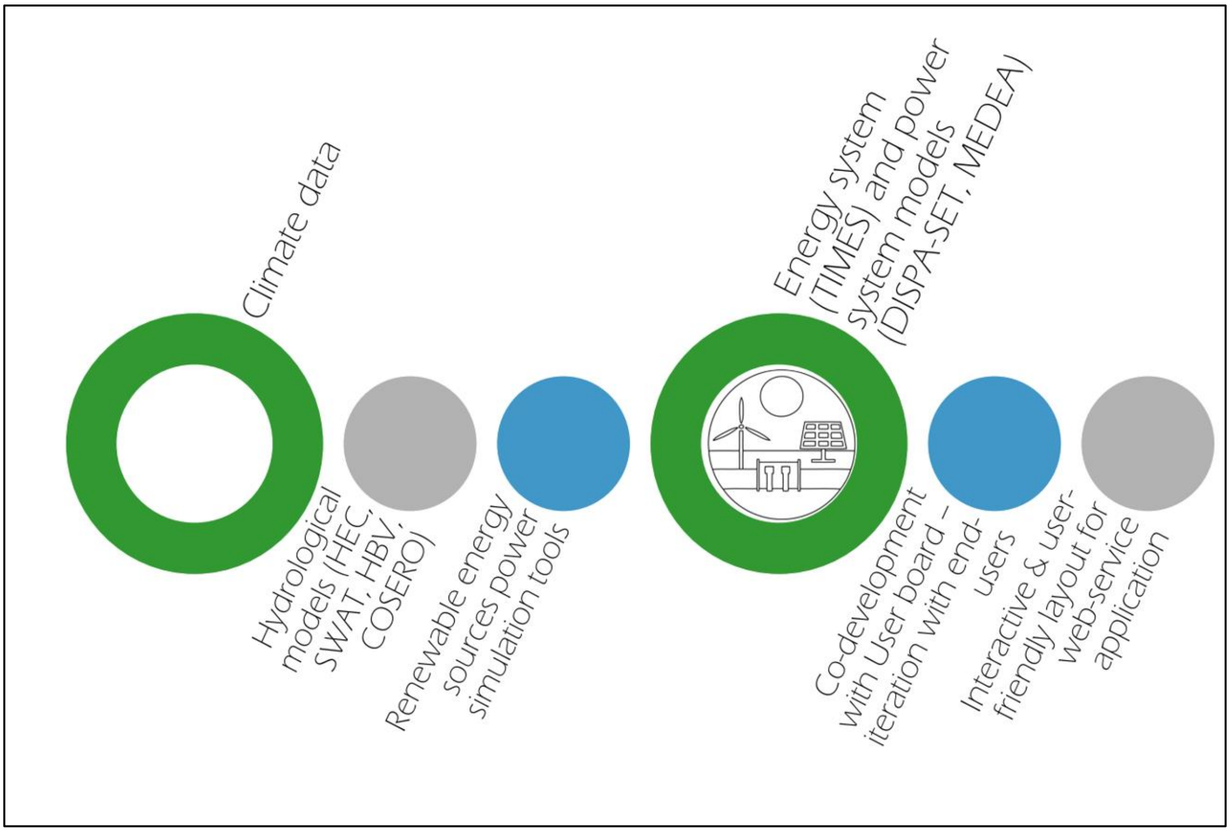

Figure 1-1: Clim2Power´s process, (“Clim2Power,” n.d.)

The BOKU University of Natural Resources and Life Sciences is a project partner of Clim2Power and focuses on the hydro sector, especially on rainfall-runoff models. To gain information about data sets and their suitability for hydrological modelling this master thesis does first research on the issue. The thesis solely concentrates on two subcatchments of the Danube in Austria and four different data sets for precipitation and temperature. Climate data for the catchment areas are analysed in order to assess and compare meteorological (re-)analysis data (“Clim2Power,” n.d.).

The main purpose of this thesis is therefore to critically investigate different data sets as potential input data for hydrological models. It will be analysed, whether the data sets have a higher agreement for larger than for smaller catchment areas, and whether the bias between the data sets are minor when a small range of elevation is characterizing the catchment. Moreover, regularities and systematic biases between the data sets will be looked for.

Chapter 2 provides background information on the different data sets that are used for the comparison and on the study area that the assessment is based on. The methodology is explained in chapter 3, where the selected statistical analyses will be outlined in detail as well. Chapter 4 lists the results and statistically describes the discrepancies between the data sets. An interpretation of these results as well as limitations to this thesis are discussed in chapter 4.4.5.

2. Data variables and data sources

Hydrological applications, climate models or environmental simulations need (gridded) data sets of temperature, precipitation, etc. as inputs. Although the requirements for the input data differ, a high quality, temporal coverage and a long-term consistency is important for all of them, as outlined in chapter 1. In Austria several meteorological data sets exist. For this thesis the focus is put on four different data sets: SPARTACUS data set, INCA data set, E-OBS data and COSMO REA 6 reanalysis data. INCA and SPARTACUS are prepared by the Austrian ZAMG (Central Institute for Meteorology and Geodynamics, Vienna, Austria), COSMO REA 6 is provided by the German DWD (German Weather Service) and E-OBS is a product of the European Climate Assessment & Data set project (ECA&D). Table 2-1 gives a summary of these data sets, which are explained in detail in the following chapter.

Table 2-1: Summary of data sets (Hiebl and Frei 2017, T. Haiden et al. 2011, Bollmeyer et al. 2015, Haylock et al. 2008)

Product	**Approach (used data)**	**Temporal coverage**	**Spatial domain**	**Spatial resolution**	**Temporal resolution**	**Reference**
SPARTACUS	Spatiotemporal Reanalysis (Interpolation with DEM and observation data)	1961-today	Austria	1x1km	daily	ZAMG, Hiebl and Frei, 2017
INCA	Integrated Nowcasting through Comprehensive Analysis (model and observation data)	2003-today (data available until 2015)	Austria	1x1km	15min (RR) 1h (T)	ZAMG, Haiden et al., 2011
COSMO-REA6	Reanalysis (NWP model and observation data)	1995-today	Europe	6x6km	hourly	DWD, Bollmeyer et al., 2015
E-OBS	Observation-only-based (interpolation)	1950-today	Europe	25x 25km)	daily	ECA&D, 2018

2.1 Precipitation and air temperature

Precipitation and air temperature are major drivers for hydrological processes, with precipitation being the most important factor in the water cycle, at least in precipitation dominated regimes. Meteorological data are used as input data and influence different components in a hydrological model. For example, evaporation rates are higher with an increasing temperature. Consequently, this thesis solely uses temperature and precipitation for the comparison, even if the data sets provide information on other parameters as well (Beck et al. 2017).

2.1.1 INCA data set

The INCA data set is prepared by ZAMG. INCA stands for **I**ntegrated **N**owcasting through **C**omprehensive **A**nalysis. The project was started in 1999 and since 2005 the system is operating. It covers Austria and the domain size is therefore 600 x 300 km. The main idea of INCA is to add corrections to direct output of numerical weather prediction (NWP) in using real-time observations and high-resolution remote sensing data for topography. Therefore, the objective is to improve forecasts up to 72 h. As shown in Figure 2-1 and explained in detail in this chapter, INCA is divided into an analysis and forecast part (ZAMG, n.d.; Karabatić, Weber, and Haiden 2011).

For a horizontal resolution of 1 km and a vertical resolution of 200 m, INCA offers hourly updated forecasts for temperature, air humidity, wind and global radiation in Austria. Moreover, every quarter of an hour, it delivers forecasts for cloudiness, precipitation and the type of precipitation all over Austria. A high resolution of 1 km allows a high accuracy based on the values of local observation stations. The precision of the system drops in steep terrains. The variables are influencing each other, with for example cloudiness analysis taken into account for nowcasting temperature (Karabatić, Weber, and Haiden 2011; T. Haiden et al. 2011).

INCA increases the accuracy of numerical forecast products in the now-casting range (<4 h) and very short range (<12 h) as well as predictions up to 72 h. Consequently, INCA is already used in flooding warning systems and flooding prognosis, as well as for detailed weather information on Internet Portals (Karabatić, Weber, and Haiden 2011).

To calculate temperature, air humidity and wind (3d) the following way is proceeded, as shown in Figure 2-1.

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- **First Guess**

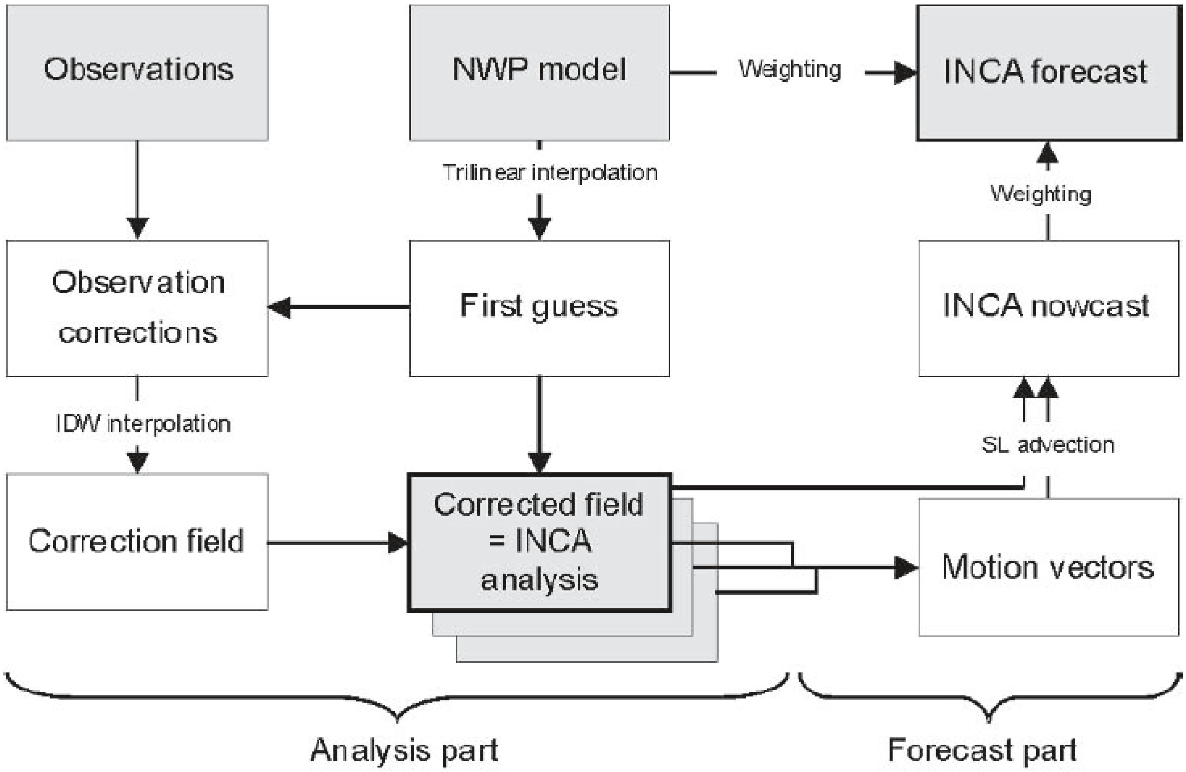

Figure 2-1: Basic structure of the INCA analysis and forecasting system (Michaelides 2008)

The weather forecast model ALADIN, which has a resolution of 9.6 km (kilometers), is interpolated to the INCA resolution of 1.0 km. Since 1999 ALADIN forecasts run twice a day, at 00:0 UTC and 12:00 UTC. Based on a specific extrapolation algorithm, it is possible to get realistic results even for the alp valleys. In the first guess, the output of an NWP model with observations corrections are used (T. Haiden et al. 2011).

- **Observation Correction**

All over Austria, ZAMG installed around 250 semiautomated observation stations, with an average horizontal distance of 18 km. The location of these stations can be seen in Figure 2-2, where the filled circles represent semiautomated observation stations and surface synoptic observation stations and open circles stand for hydrological stations.

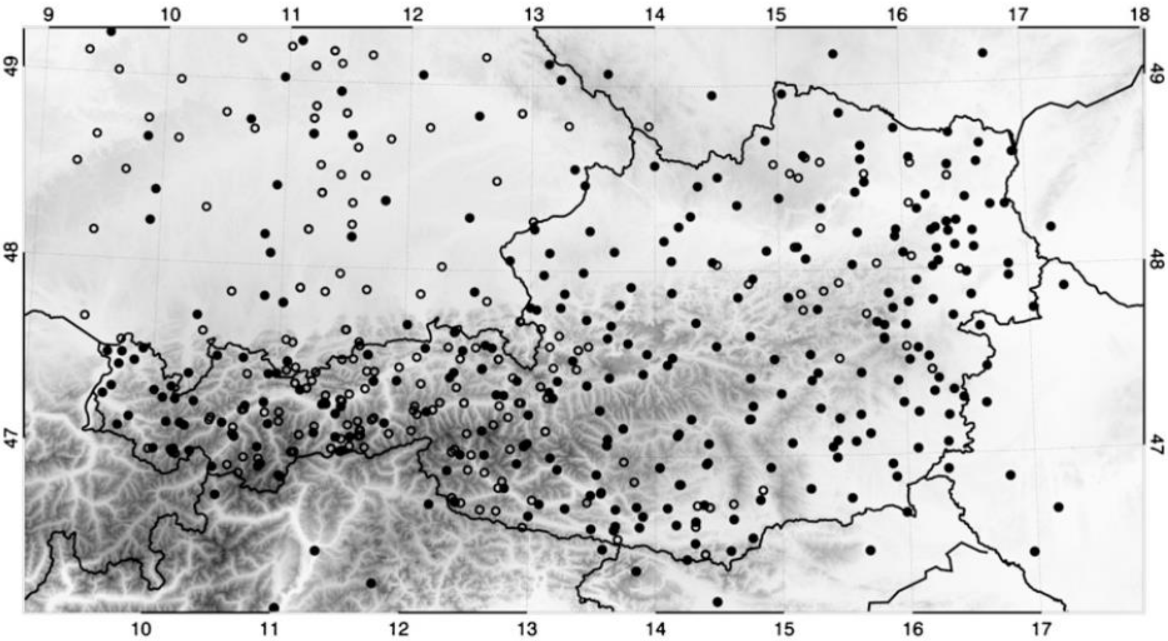

Figure 2-2: Observation stations used for hourly values in INCA (T. Haiden et al. 2011)

Although the stations are mostly located in the valleys, the stations cover most of the topographic range, as there is a reasonably enough number of stations up in the mountains (T. Haiden et al. 2011).

At the observation station the difference between the “First Guess” and the current observation is computed, in order to trilinearly interpolate with a three-dimensional correction field. The spatial distribution and the atmospheric stability are spatially interpolated, in using inverse distance weighting in geometrical and physical space. With the calculated value, the “First Guess” is then corrected. This result is the INCA-Analysis (T. Haiden et al. 2011).

- **Nowcast**

  The difference, which is calculated in the “Observation Correction”-step is also used to correct the ALADIN-prognosis for the following hours.

To calculate precipitation, precipitation type, global radiation and cloudiness the following way (2d) is proceeded:

- **Analysis**

  Data from the observation stations are combined with data from remote sensing. These combinations use the good quantitative accuracy of the station data and the good spatial resolution of the remote sensing data. Different radar stations and satellite data are used for remote sensing. With inverse distance weighting, the data are interpolated to the INCA grid.

  According to Haiden et al. precipitation predicted by INCA can be trusted and used in areas, where the radar coverage is unsatisfactory, but the density of observation stations is good enough. Due to the topography in Austria, the radar data have generally a low quality, especially during wintertime and in mountainous western Austria (T. Haiden et al. 2011).

- **Nowcast**

  With consecutive analysis and correlation methods a vector can be calculated, which helps estimating precipitation and cloudiness over the next hours. In this work, no nowcasting products are used (ZAMG, n.d.; Thomas Haiden and Steinheimer 2007)

2.1.2 SPARTACUS data set

The SPARTACUS data set has been available since 2016 and covers the time back to 1961. It has a grid spacing of 1 km and it is constantly updated. The temporal resolution is 24 hours. SPARTACUS delivers minimum and maximum air temperature and precipitation sum. It was developed for climate monitoring and especially to represent interannual variations and change for different sector, such as hydrology, hydropower and water resources. The observation data are carefully chosen to guarantee high spatial resolution and stable coverage of input data over time (Hiebl and Frei 2017).

2.1.2.1 Maximum and Minimum Temperature

SPARTACUS uses collected data from observation stations and interpolates them between the stations. The main purpose of SPARTACUS is to achieve best consistency of gridded long-term data with a daily resolution, that are well adapted to high mountain regions. SPARTACUS is based on a relatively new spatial interpolation: the methodology of Frei which was originally applied in 2014 for Switzerland. This methodology focuses on complex topography and mountainous regions and only applies observation data and a digital elevation model to the interpolation. With the Alps being a part in Austria, this country shows a similar topography to Switzerland and therefore Frei´s methodology was considered as being suitable as well. Adjustments were generated, so that the interpolation method fits better to the geography and network density in Austria (Hiebl and Frei 2017).

SPARTACUS uses 150 station series in and around Austria to interpolate the gridded data, shown in Figure 2-3. 112 stations are located in Austria, where the minimum and maximum air temperature data are collected. 38 stations are used from neighbouring countries to achieve high quality results in the border areas of Austria. In the map downward triangles show locations which tend to have cold-pools. An upward triangle identifies a summit station and a diamond represent an inner-city station. The remaining stations are marked with a circle. The colours display the subregions that are needed for the vertical temperature profiles (Hiebl and Frei 2017).

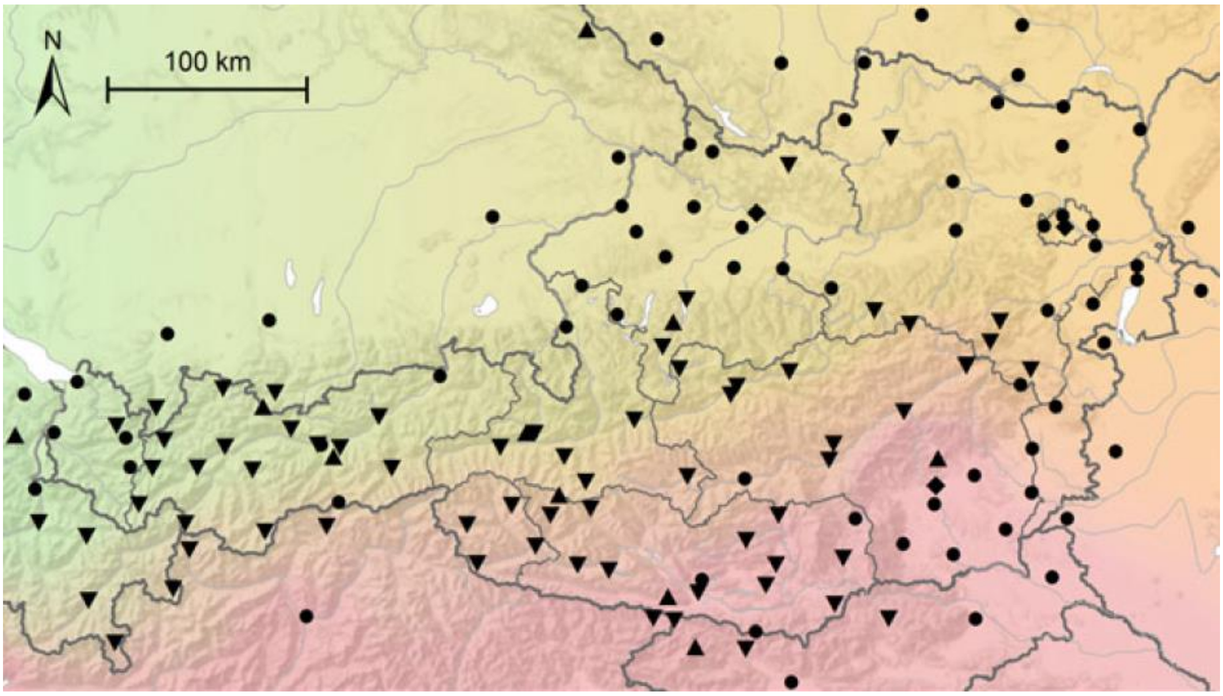

Figure 2-3: Observation stations SPARTACUS – temperature (min, max) (Hiebl and Frei 2017)

All Austrian stations either have a complete data set from 1961 to presence or have a maximum of 5 % of gaps in the data series. Interpolation fills the gaps, by using the three best correlating neighbouring stations. The validation of the data set revealed the following: there is a relatively higher error in the minimum than the maximum temperature. SPARTACUS works better for flatlands than for the interior of the Alps, and the error in winter is relatively larger compared to the summer. In inner-Alpine valleys the minimum temperature tends to be overestimated and random errors appear to be larger. Hiebl and Frei (2017) averaged the mean absolute error over all stations and the results shows that the daily minimum temperature has a mean error of 1.1°C and the bias for the daily maximum temperature is 1.0°C. All in all the quality of the results are comparable to data sets like INCA (Hiebl and Frei 2017).

Frei´s interpolation method was created for use in environmental modelling and climate research. Common nonlinearities are well computed, for example contrasts and nonlinearities in vertical thermal structure. The method is based on overlaying background and residual temperature fields. For the background data focus is put on large scale horizontal changes and on a vertical temperature profile that is based on topography. The residual temperature fields cover regional variations like valley-scale cold poles. It is created by using the deviations from the background field and weighting them. So-called non-Euclidean distance metric is used. The purpose of non-Euclidean distance metric is to identify and accurately consider topographic barriers on horizontal change of air masses (Frei and Hiebl 2016; Frei 2014).

2.1.2.2 Daily Precipitation Sum

SPARTACUS uses a similar strategy for calculating the daily precipitation sum as for calculating the minimum and maximum temperature. The observation stations are carefully chosen, so that the data are as homogeneous as possible and that there are (nearly) no gaps from 1961 to present in the selected observation stations. Altogether 566 stations are used to base the interpolation on. 523 stations are located in Austria and 43 are installed in neighbouring countries. 115 observation stations in Austria are maintained by ZAMG and 408 are serviced by provincial hydrographical services. Figure 2-4 shows the observation stations that are used for the interpolation. Stations that are marked by black and blue dots and light blue triangles are needed for the mean monthly precipitation interpolation. Black dots show the station that are part of the daily precipitation sum interpolation. In general dots represent conventional rain gauges whereas triangles symbolize totalizers. Evaluation is demonstrated by grey color gradation as seen on the right side of Figure 2-4. (The red frame indicates the area that was used for evaluating SPARTACUS and is of no importance to this thesis.) (Frei and Hiebl 2016).

The methodology for calculating the daily precipitation sum is divided in two separate main steps. First, the mean monthly precipitation is interpolated using Kriging with an external drift. This provides the background fields. Second, the daily relative anomalies

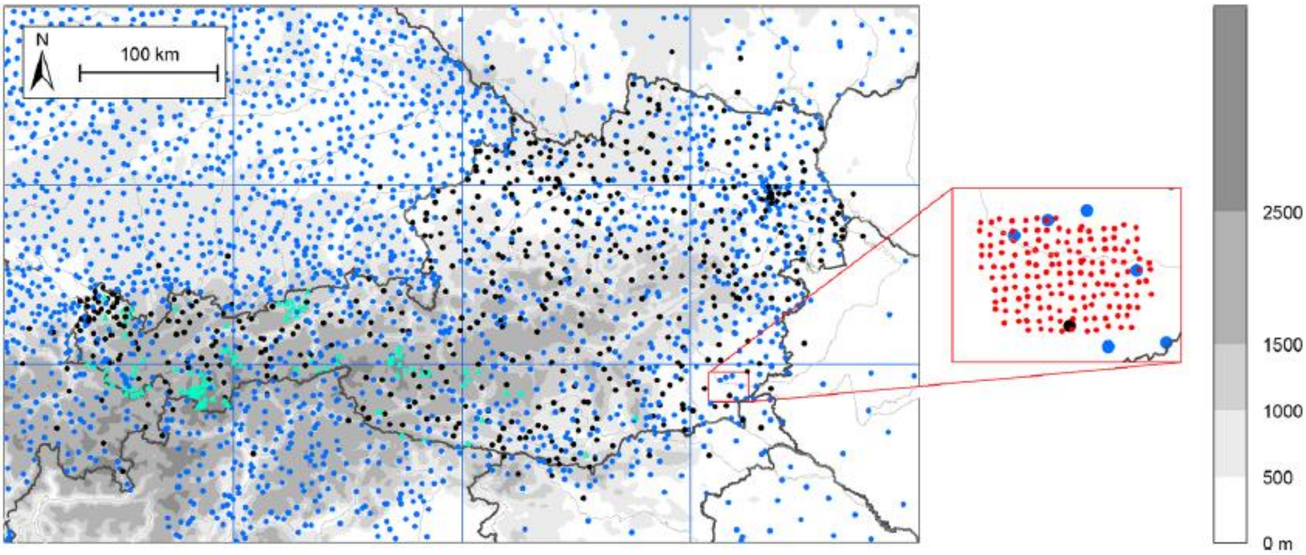

Figure 2-4: Observation stations Spartacus – daily precipitation sum

are computed, using angular distance weighting. The SPARTACUS gridded data for precipitation provides some limitations. Uncertainties are given since precipitation is generally underestimated for this data set. The reason for this phenomenon can be found in measurement errors, such as wind or wettings effects. The error is correlated to the station´s location and is between a few percent in summer, and if there is no wind. If stations are wind and snow exposed and at a high elevation level, the error can be higher than 50% as seen in **Fehler! Verweisquelle konnte nicht gefunden werden.**. (Herrnegger, Nachtnebel, and Schulz 2015)

Table 2-2: Systematic errors in precipitation measurements (Herrnegger, Nachtnebel, and Schulz 2015)

Systematic error	Mangitude
Wind-induced errors	2–10% (liquid precipitation) 10– >50% (snow)
Wetting losses	2–10%
Evaporation losses	0–4%
Splash-out and splash-in	1-2%
Fog and dew	4-10%

Furthermore inhomogeneity – which is described in detail in chapter 2.1.4 – is another factor that leads to inaccuracy within the results. The quality of the data generally depends on the interpretation. If the grid point values are used as a mean value for a certain area, errors get smaller. However, if the grid points are interpreted as point estimates, the results can be around 1.5 times of the station's observation values and they deviate even more in high elevation areas and in summer. Point estimates differ less in flatlands and in autumn and winter. Hiebl and Frei come to the conclusion that SPARTACUS works better on a large scale than for small-scale processes and interpretation (Hiebl and Frei 2017).

2.1.3 COSMO-REA6

COSMO-REA6 is based on Consortium for Small-Scale Modelling (COSMO) which is a numerical weather prediction (NWP) model, developed by the German Meteorological Service. COSMO-REA6 is a regional reanalysis product that ranges over the European CORDEX EU11 area as shown in Figure 2-5. The resolution is 0.055°, so the grid cells for COSMO-REA6 are around 6x6km with 40 vertical levels. A temporal output of 1 hour is available (Bollmeyer et al. 2015).

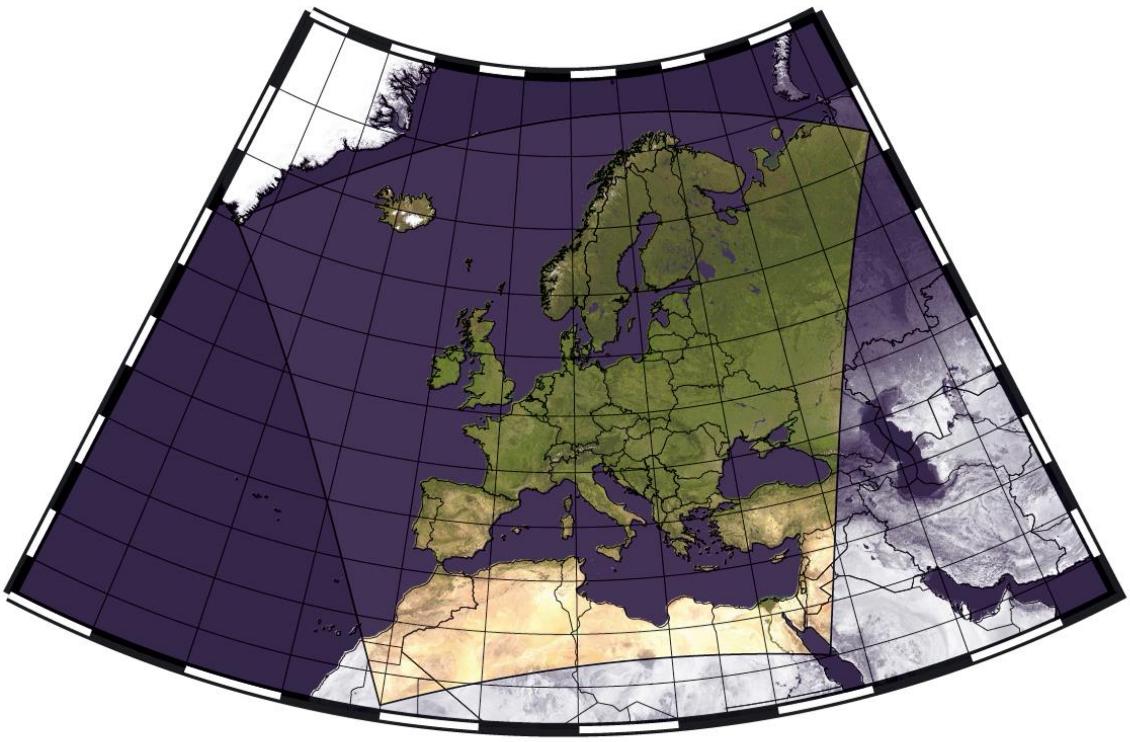

Figure 2-5: Scope COSMO-REA6 (Bollmeyer et al. 2015)

COSMO is a numerical weather prediction model and has been designed for the meso-β-scale and the meso-γ–scale, meaning that meteorology in the order of 2 to 200 km can be represented. For the meso-β-scale this includes for example cloud lines and for the meso-γ–scale it covers thunderstorms, urban effects, etc. Based on the mesoscale, it is expected that COSMO-REA6 can compute important weather phenomena better than other reanalysis products and that the effects of orography are described better (Orlanski 1975).

As explained before, reanalysis products use NWP models and implement them with data assimilations that use information from meteorological observations to get three-dimensional atmospheric information about past time series. The most famous reanalysis systems are ERA-Interim and ERA-40. A three-hour update of ERA-Interim is used for the boundary conditions for COSMO-REA6 as shown in Figure 2-6. This is needed as the system is limited to a certain area. In order to guarantee an integration to the environment boundary conditions are required (Bollmeyer et al. 2015).

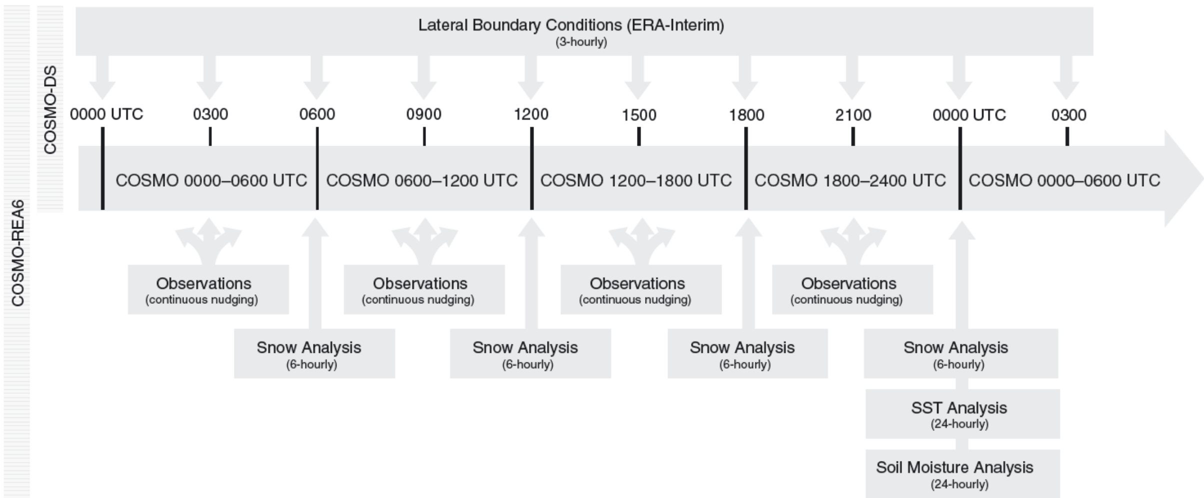

Figure 2-6: COSMO-REA6: process cycle (Bollmeyer et al. 2015)

Compared with other reanalysis products, COSMO-REA6 offers a very high spatial and temporal resolution. The continuous data assimilation in COSMO-REA6 is completed with so-called nudging or Newton relaxation, where the calculated values converge to observation data. The data assimilation is the same as applied to COSMO. Different systems, like radiosondes and aircrafts contribute to the observation data for the data assimilation (Bollmeyer et al. 2015).

Bollmeyer et al. (2015) tested the quality of COSMO-REA6 and compared it with different (reanalysis) products. The most important findings are described in the following.

Looking at year-round precipitation COSMO-REA6 highly overestimated precipitation in northern countries like Scandinavia, Russia and Iceland. In part of the Alps, Turkey and Scotland the overestimation error is marginally lower. The precipitation sum is slightly underestimated in mid and south Europe. Concentrating on a diurnal cycle the highest precipitation rate of the day in summer is modelled too late, in comparison with measured data, which leads to the conclusion that convective rainfall events start delayed in COSMO-REA6. In comparison to other global reanalysis products, COSMO-REA6 works relatively well for heavy precipitation events. However, a general small underestimation of high precipitation events can be found. Compared with ERA-Interim it is obvious that small-scale events are better reproduced in COSMO-REA6 (Bollmeyer et al. 2015; Springer et al. 2017).

2.1.4 E-OBS data set

The E-OBS data set is the observation-only-based gridded version of the ECA&D data set, which is a product of the European Climate Assessment & Data set project (ECA&D). ECA&D is funded by the EU and the project is a collaboration of meteorological institutes and universities. Daily, land-only data are available, starting in 1950 and they spatially cover Europe and the Mediterranean area. E-OBS is the first data set that is publicly available for whole Europe.

The downloadable data are the following: daily mean temperature (TG), daily minimum temperature (TN), daily maximum temperature (TX), daily precipitation sum (RR), and daily averaged sea level pressure (PP). Four different grid versions are provided: 2 regular latitude-longitude (0.25 and 0.5 degree) grids, and 2 rotated pole grids (0.22 and 0.44 degree). The grid is an interpolation of observation data from an EU-wide network of meteorological station, using kriging and the monthly mean for the interpolation. It is possible to download a table with the observation stations. Altogether 11422 stations can be found for the grid data, however not all of them provide data for all interpolated variables. For Austria there are only six stations used for the E-OBS data. The names, numbers, latitude, longitude and elevation are listed in Table 2-3 (“ECA&D” 2018).

Table 2-3: Austrian stations used in E-OBS

Station	Station Name	Latitude	Longitude	Elevation
11	Kremsmünster	48.05	14.13	383
12	Graz	47.08	15.45	366
13	Innsbruck	47.27	11.4	577
14	Salzburg	47.8	13	437
15	Sonnblick	47.05	12.95	3106
16	Wien	48.23	16.35	198.5

For this master thesis version 17.0 of the E-OBS data were used, which was released in April 2017. The data were downloaded in a NetCDF format.

As the data are interpolated there are two major problems that need to be considered: If there are errors in the stations – f.e. an incorrect station location information – they influence the interpolation as the errors are passed on. Another problem is that inaccuracies are developed due to a minor density of observation stations. All in all accuracy decreases with less stations, especially if the terrains are complex with a high change in altitude and if the variable is highly spatially distributed (Hofstra et al. 2009).

Hofstra et al. (2019) tested E-OBS gridded data to show how E-OBS data are limited. As this master thesis compares different data types it is important to know in advance, where the limits of the different data are, so that the right conclusions can be drawn. For the evaluation Hofstra et al. (2019) tested the data in different ways. Two out of the three tests are shortly summarized in the following subchapters, due to their significance to this thesis (Hofstra et al. 2009).

(In-)homogeneity

Long term data are often falsified due to changes in station location, observing practises, instruments, etc. leading to so-called inhomogeneities in the data series. EOB-S uses data from different institutes, so inhomogeneities are not consequently edited. Data with possible inhomogeneities are flagged, but they are still used for the interpolation in E-OBS as a high density of stations is needed for the interpolation. Hofstra et al. used the so-called Wijngaar method to identify inhomogeneities. Emphasis was put on categorizing the gridded data in useful, doubtful and suspect areas, however the effectiveness of the test was not analysed (Hofstra et al. 2009).

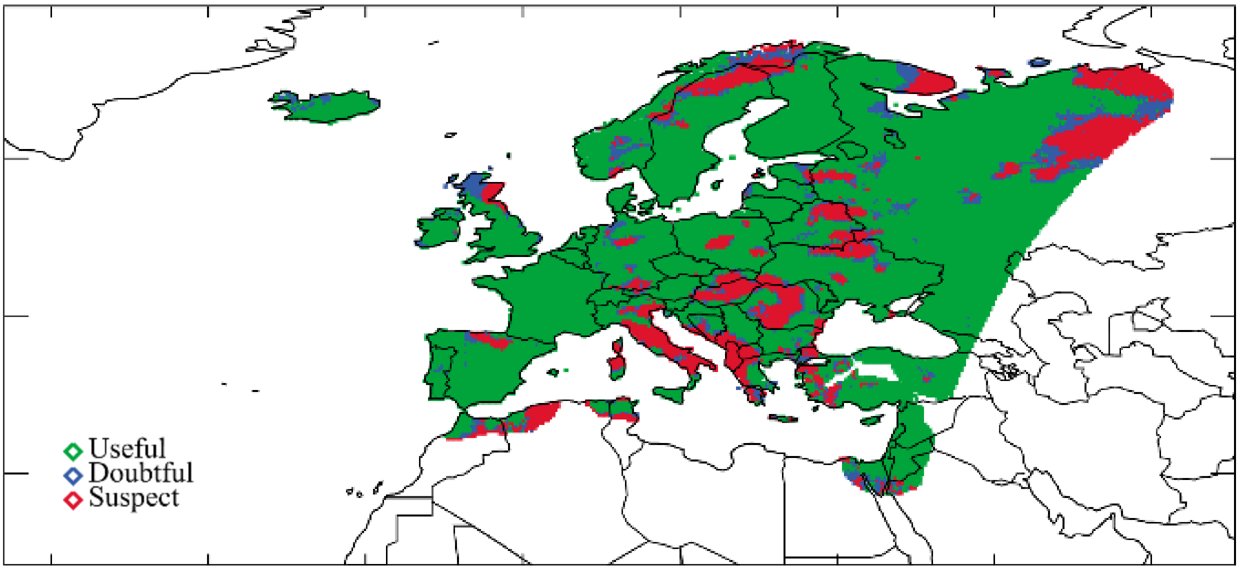

Figure 2-8: Homogeneity of the gridded data for precipitation (Hofstra et al. 2009)

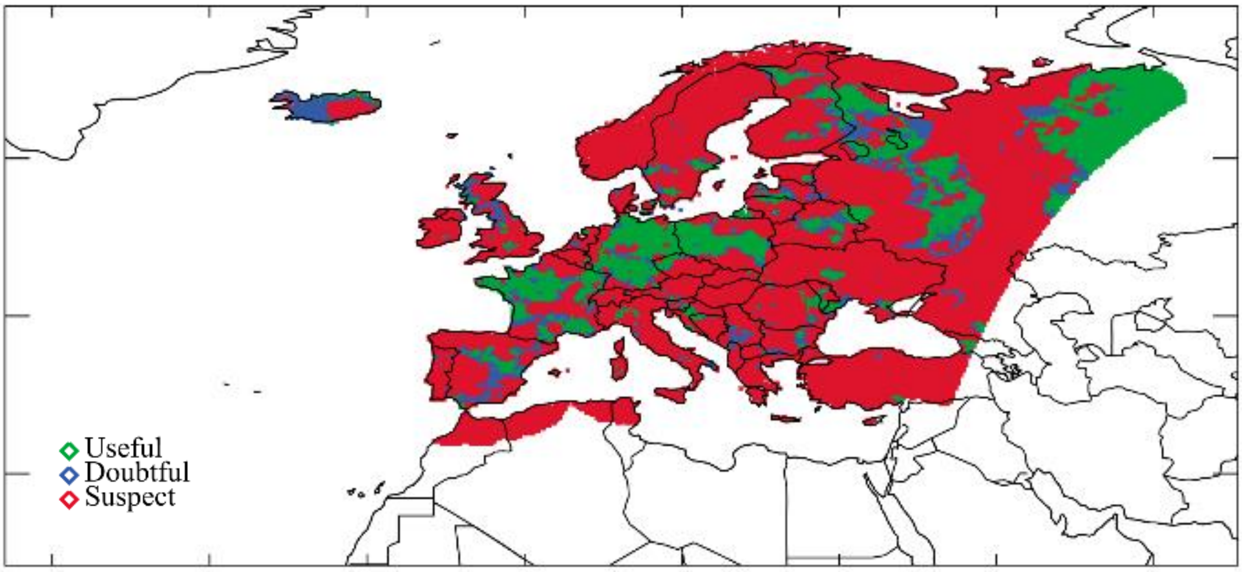

Figure 2-7: Homogeneity of the gridded data for temperature (Hofstra et al. 2009)

Figure 2-8 and Figure 2-7 show the results of the test: the potential inhomogeneous grid boxes. It is obvious that the E-OBS precipitation data are far more useful than the temperature data. For the catchment areas Ybbs and Salzach – which are used for the comparison as explained in chapter 2.1.4, the precipitation data appear to be useful. Temperature is only partly useful for Salzach and suspect for Ybbs. Whether the gridded data are homogeneous or inhomogeneous highly depends on the homogeneity of the stations, which were used for interpolation. In the paper it is recommended that for trend analysis – especially when the focus is put on extremes – only homogeneous areas are to be used (Hofstra et al. 2009).

Density of observation stations

For this test, statistical values – like R^2 and root mean squared error – from different gridded data sets and the E-OBS data set were compared. The compared data sets all use interpolations with a denser station network. The findings reveal that E-OBS shows higher errors in mountain regions. Precipitation is most accurate in winter whereas temperature works best in spring. Altogether it can be stated that E-OBS data show a higher accuracy for mean values than for extremes. The difference for extremes in precipitation is larger than for temperature (Hofstra et al. 2009).

In 2018 a new paper was published by Cornes et al. who describe the latest version of E-OBS gridded data set. Although it is more developed than the E-OBS data set that Hofstra et al. (2019) describe, it still shows similar limitations. Cornes et al. (2018) emphasise that due to inhomogeneity E-OBS data should be carefully used for studying long-term trends (Cornes et al. 2018).

According to Raimonet et al. (2017) E-OBS does not show a good spatial representation. The efficiency of the model that the data are used for as input, decreased in mountainous regions due to the limited numbers of observation stations. Hiebl and Frei compared specific events and come to a similar conclusion: that E-OBS is not suitable for reproducing regional details and small-scale character for daily precipitation, as it is based on a coarse grid spacing and a small number of observation stations (Raimonet et al. 2017; Hiebl and Frei 2017).

2.2 Study area

For the research area of this master thesis two catchments are chosen: Ybbs and Salzach, which are subdivided into smaller areas. The subcatchments are nested, so that the biggest catchments cover the small ones. Figure 2-9 shows a map of Austria and the geographic location of the catchments. Figure 2-10 and Figure 2-11 represent the area, elevation and location of the subcatchments. Both Ybbs and Salzach discharge into the Danube, which ends in the black sea. The following chapter outlines the most important facts of these catchments. The hydrological atlas of Austria provides information on the subcatchments. A lot of knowledge about the water cycle is covered in the atlas, however only a few data sets are put to account in this chapter. The data is listed and might help to understand differences in the meteorological data sets that will be analysed in chapter 4. The digital hydrological atlas offers shapefiles to work on. Using ArcGIS[1] the shapefiles of the hydrological atlas are clipped to the extent of the catchments. Afterwards the results are weighted to find mean values for every subcatchment. As the atlas covers Austria, the Salzach catchment is not completely located within the extent and the German parts of the catchment are not represented. However, the mean value is supposed to rightly stand for the whole catchment (BMLFUW 2007).

The project of the atlas started in 1997, with the BOKU institute of water management, hydrology and hydraulic engineering being the project leader. The time series data of the hydrological atlas has not been updated over the last years, with most of the maps covering the period of 1950-2000. Nevertheless, the data sets give a first impression of the area and its surroundings (BMLFUW 2007).

[1] ArcGIS and ArcMap, ESRI products

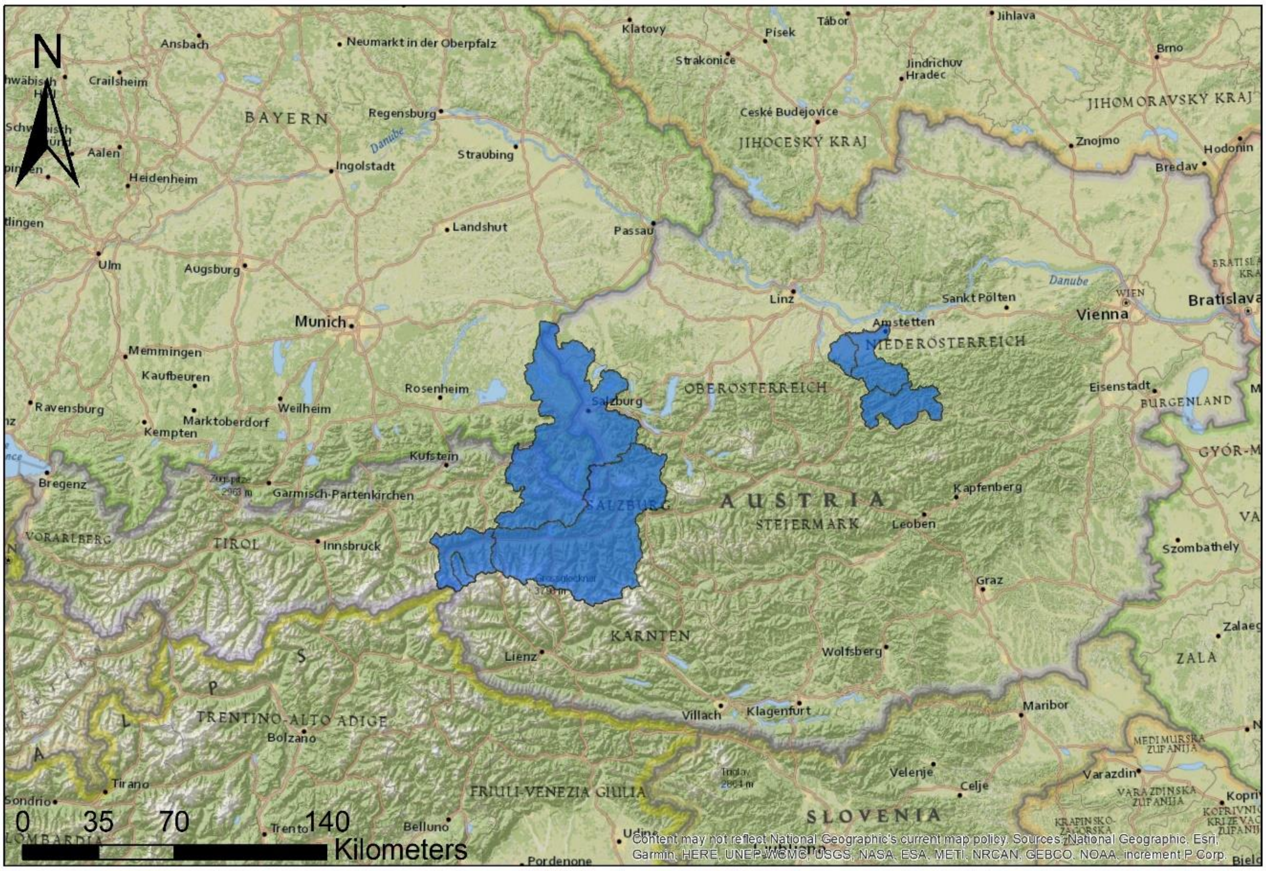

Figure 2-9: Overview of Austria and the research catchments

2.2.1 Catchment area Salzach

With a catchment area of nearly 6700 km² the Salzach River drains a great part of the Eastern Alps. The Salzach River originates in the Kitzbühler Alps at a height of 2300 m.a.s.l. and forms the boundary between Salzburg (AT) and Bavaria (DE). Its length is 225 kilometres, making it to one of the longest rivers in the Alps. The Salzach River drains into the Inn – a right tributary of the Danube – near Burghausen with a mean discharge of 250 m³/s. Over a length of 59 kilometres, it forms the boundary between Germany and Austria. The height difference within the catchment can be seen in Figure 2-10. As the altitude of the Catchment ranges over more than 3000 m, the climate conditions range from high mountain regimes in the upstream areas to a moderate continental zone in the downstream areas. The highest point is Großvenediger with over 3600 m.a.s.l. and the river mouth is at 389 m.a.s.l. (Österreichs-E-Wirtschaft 2016).

Part of the Salzach catchment is protected by the National Park Hohe Tauern, with the highest areas being coved by glaciers and permafrost. Cultural landscapes and tourism in summer and especially in winter have strongly shaped the area. The City of Salzburg is the biggest centre and most people live in the city and its surroundings. Due to the geographic exposition and climate conditions extreme floods, landslides, avalanches and flash floods highly threaten this area. In the northern parts high precipitation events occur because of the blocking effect of the Alps (Kienberger, Lang, and Zeil 2009).

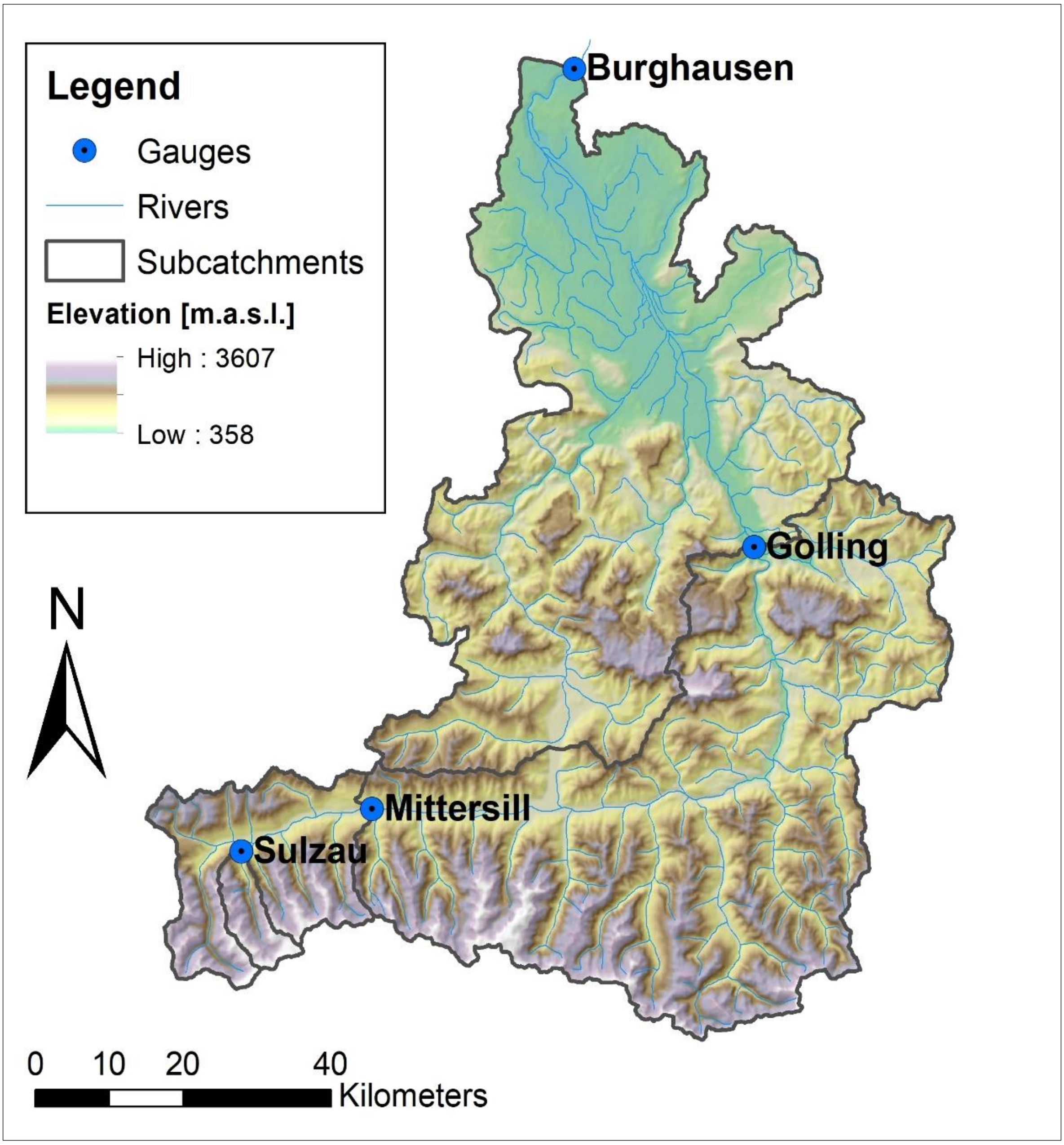

Figure 2-10: Catchment Salzach

Figure 2-10 shows the Salzach catchment, the river network and the division of the four subcatchments that the calculations are based on: Sulzau, Mittersill and Golling. The subcatchments vary in area and height. Since SPARTACUS does not cover the German part of the Salzach, the comparison for the overall Salzach catchment (Burghausen) is excluded. The overall Salzach catchment is still shown in Figure 2-10. As explained, the subcatchments are nested so that Burghausen covers all other catchments.

Table 2-4 displays the land use in the subcatchments of Salzach, as found in the Hydrological Atlas of Austria. Especially in the very high regions (Sulzau, Mittersill) glaciers play an important role. As this table is not up-to-date, it is expected that there is a shift from area covered by glaciers to area poor on vegetation and grassland. In the lower regions of the Salzach catchment, grassland and forests are the main land cover (BMLFUW 2007).

Table 2-4: Land cover - Salzach (BMLFUW 2007)

Subcatchment	Sulzau	Mittersill	Golling
Grassland [%]	13.7	32.5	38.2
Forests [%]	15.4	29.7	42.3
Areas poor on vegetation [%]	45.5	28.5	15.6
Glaciers [%]	25.4	8.7	3
High-density Residential Area [%]			
Low-density Residential Area [%]		0.7	0.6
Open water [%]			0.3
Wetlands [%]			

The area and elevation of the subcatchments as well as mean annual air temperature, precipitation, evapotranspiration and days of snow cover are shown in Table 2-5. As expected, the lower the elevation the higher is the mean annual air temperature and mean annual evapotranspiration. Furthermore, mean annual precipitation rises in higher areas. The whole catchment area of the Salzach, which is looked on in this thesis, is 6689.7 km². Sulzau has the highest elevation and smallest area (BMLFUW 2007).

Table 2-5: Data Hydrological Atlas – Salzach (BMLFUW 2007)

Subcatchment	Sulzau	Mittersill	Golling
Area [km²]	80.8	590.2	3553.9
Mean elevation [m.a.s.l.]	2301	1854	1511
Mean annual air temperature [°C]	-0.66	1.85	3.28
Mean annual precipitation [mm]	1901.9	1574.3	1444.0
Mean annual areal actual evapotranspiration [mm]	276.5	379.1	451.6
Mean annual duration time of snow cover [days]	268	224	194

2.2.2 Catchment area Ybbs

The size of the Ybbs catchment area is around 1000 km². North of the mountains “Großer Zellerhut” and “Dürrenstein”, the Ybbs River originates near Maria Zell. Its length is 138 kilometres and it ends in the Danube at 224 m.a.s.l. – near the town Ybbs. The height difference between its origin and its outlet is around 1000 metres. Ybbs is a right tributary of the Danube (Eberstaller-Fleischanderl 2011).

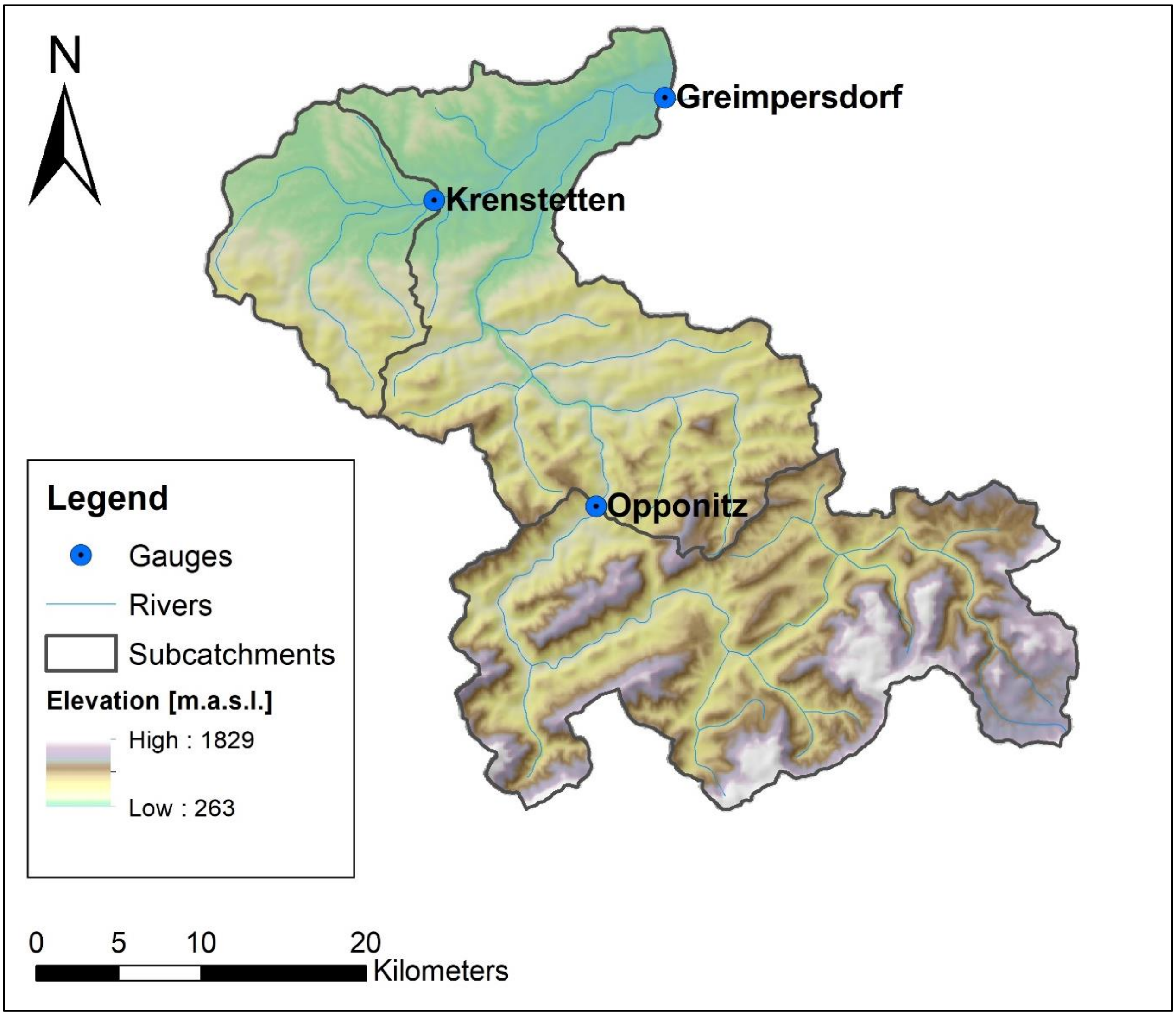

Figure 2-11: Catchment Ybbs

Figure 2-11 shows the Ybbs catchment, the river network and the division of the three subcatchments that the calculations are based on: Opponitz, Krenstetten and Greimpersdorf. The subcatchments vary in area and height. As explained, the subcatchments are nested so that Greimpersdorf covers all other catchments.

Table 2-6 lists the percentage of different land use categories in the Ybbs subcatchments as found in the Hydrological Atlas of Austria. According to the Atlas, the main part is covered by forests and grassland. In comparison to the Salzach, there are no glaciers in the Ybbs catchments (BMLFUW 2007).

Table 2-6: Land use - Ybbs (BMLFUW 2007)

Subcatchment	Opponitz	Greimpersdorf	Krenstetten
Grassland [%]	13.1	40.8	73.4
Forests [%]	86	55.4	13.3
Areas poor on vegetation [%]	0.4	0.2	
Farmland [%]		1.8	11.5
High-density Residential Area [%]		0.3	
Low-density Residential Area [%]	0.4	1.4	0.7
Open water [%]	0.1	0.1	

The area and elevation of the Ybbs subcatchments as well as mean annual air temperature, precipitation, evapotranspiration and days of snow cover are shown in Table 2-7. As this catchment is located at a lower elevation than Salzach catchment, the mean annual air temperature and the mean annual evapotranspiration are higher. There are less days of snow cover in this area. The whole catchment area of the Ybbs that is looked on in this thesis, is 1116 km².

Table 2-7: Data Hydrological Atlas - Ybbs

Subcatchment	Opponitz	Greimpersdorf	Krenstetten
Area [km²]	506.5	1116	156.7
Mean elevation [m.a.s.l.]	919	521	438
Mean annual air temperature [°C]	5.54	6.79	8.10
Mean annual precipitation [mm]	1634.3	1347.0	959.3
Mean annual areal actual evapotranspiration [mm]	601.3	620	637.4
Mean annual duration time of snow cover [days]	135	105	71

3. Development of tools for comparing and assessing different data sets

This chapter describes the workflow and statistical methods in order to achieve results, on which the interpretation and conclusion are based on.

3.1 Aggregation of data sets to catchment level

As described in chapter 2 four different data sets covering Austria are used for the comparison: SPARTACUS, INCA, COSMO-REA6 and E-OBS. For each data set the following information was available: gridded, daily weather data between 2003 and 2015. The daily weather data include precipitation and mean temperature.

In a first step the catchments Ybbs and Salzach were chosen for research and divided into subcatchments using ArcGIS[2]. The purpose of the subdivision is to get an understanding of how well the data sets work, depending on different elevation and subcatchment size. Next, the gridded data sets were clipped to the extent of the (sub)catchments. For the INCA data set the intersection tool in ArcGIS was used, to aggregate the information on the catchment area as shown in Figure 3-1. With the intersected files a unique value for both variables (precipitation, temperature) at every time step and each (sub)catchment was calculated.

[2] ArcGIS and ArcMAP, Esri products

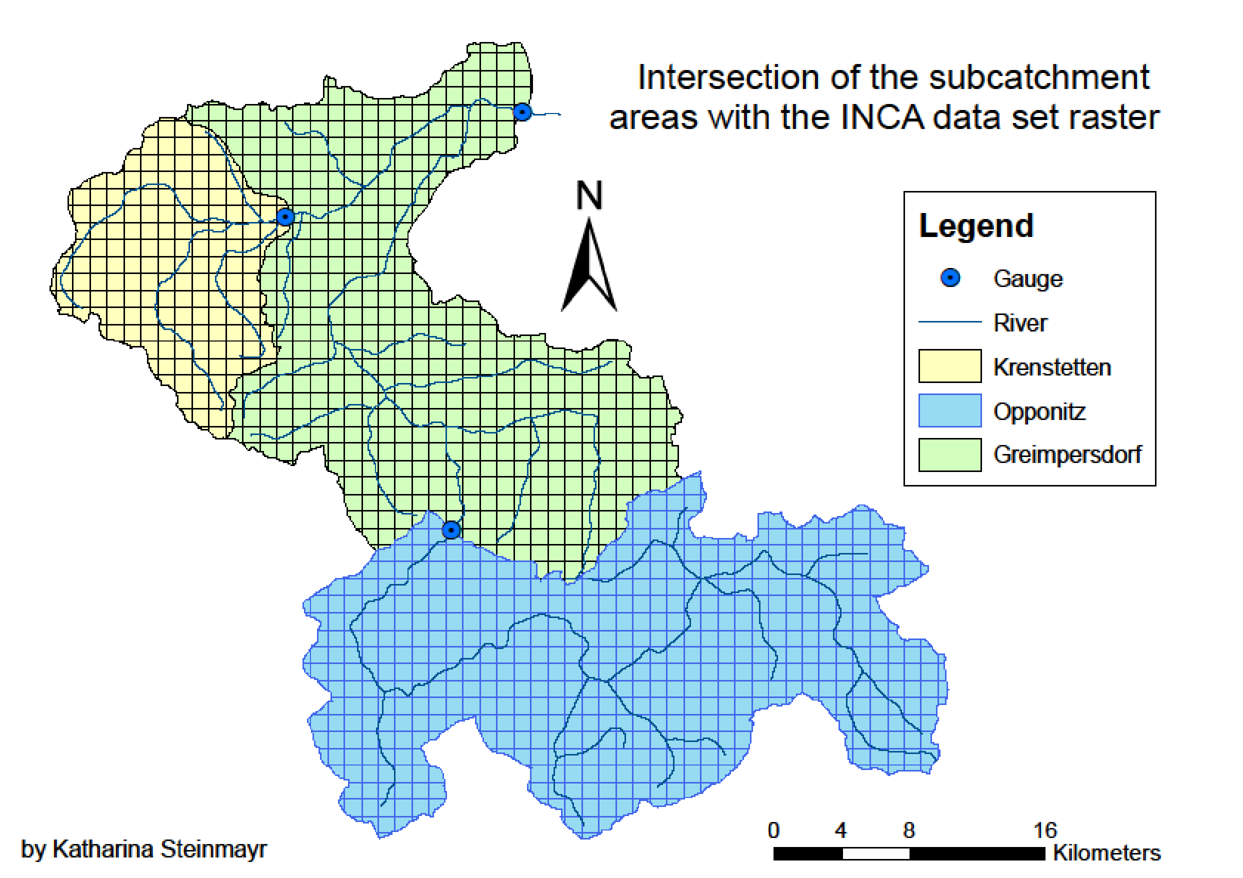

Figure 3-1: Intersection INCA data set raster and subcatchments

For SPARTACUS, COSMO-REA6 and E-OBS the gridded data were available in a netCDF file format. To extract the information from the netCDF-files and aggregate it to the extent of the catchments, the Institute of Hydrology and Water provided a function in R[3] called “aRastoCAT”. “aRastoCAT” was developed by Christoph Schürz. For using this function, it was necessary to specify the coordinate system, the variables and years that are of interest, as well as the area that the information should be aggregated on. Finally, the result of these first steps was a table for each of the four data sets precipitation and temperature data for every subcatchment. While for E-OBS, INCA and COSMO-REA6 continuous data for the whole catchments were available, the results in SPARTACUS average the data, without having the information over Germany.

[3] R for statistical computing

In the second step, the different data sets are compared. Significant values and statistic parameters are calculated to provide a first impression of the differences. Afterwards, diagrams are created to graphically demonstrate variation and consistency.

Although all data sets are based on interpolation, SPARTACUS is supposed to be the most accurate, based on experience of the supervising institute. Therefore, statistical parameters – like correlation – are calculated using SPARTACUS as reference.

3.2 Summary statistics on temporal data series

In 2018 an article was published in the International Journal of Climatology about “Assessing reliability of precipitation data over the Mekong River Basin: A comparison of ground-based, satellite, and reanalysis data sets.” The article was used as a guideline and the statistics calculated are based on it (Chen, Chen, and Azorin-Molina 2018).

Statistical values are calculated for precipitation and temperature, covering: mean, standard deviation (sd), median, absolute bias, coefficient of determination (R^2) and root mean squared error (RMSE). The values are computed on a long-term annual basis and for summer and winter seasons. The summer months cover June, July and August (JJA) whereas the winter months include December, January and February (DJF). Focusing separately on winter and summer helps to understand for which conditions the data sets work best. A definition for the chosen statistical values is listed in this chapter. The results can be found in 4.1

Mean

The mean is described by Equation 3-1, with x_i being one single value in the data set, n being the total number of values in each data set, and $\bar{x}$ being the mean. According to the equation, all values are summed up and divided by the number of values. The mean is the average number in the whole data set (Strelec et al. 2013).

Equation 3-1: Mean (Strelec et al. 2013)

$$\boxed{\bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i}$$

Standard Deviation (SD)

The standard deviation is explained by Equation 3-2. It is the square root of the variance, which is the average value of the summed up squared differences between a value and the mean of the data set. The standard deviation helps to understand how the values are dispersed around the mean. Consequently, a high standard deviation tells that the data are highly scattered around the mean of the data set.

Equation 3-2: Standard Deviation (Strelec et al. 2013)

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

Relative Bias

The relative bias is calculated by using the hydroGOF-function in R. Equation 3-3 explains how the bias is calculated. S stands for the simulated values (INCA, COSMO-REA6, E-OBS) and O are the observed values, which for this thesis is SPARTACUS. The absolute bias between the data sets and SPARTACUS are calculated, divided by the sum of SPARTACUS and multiplied by 100 to get the percentage. With the percent bias, the average tendency of the data sets over all years is presented (Zambrano-Bigiarini 2017).

Equation 3-3: Relative Bias (Zambrano-Bigiarini 2017)

$$PBIAS = 100\frac{\sum_{i=1}^{N}(S_i - O_i)}{\sum_{i=1}^{N} O_i}$$

Absolute Bias

The bias for every day between SPARTACUS and all other data sets is calculated and the average values are listed in chapter 4.1 .The results for summer and winter are the same as seen in the boxplots for the seasonal residuals, which will be explained in the next chapter.

Coefficient of determination

The coefficient of determination (R^2) is calculated by dividing the dispersion of the residuals between two data sets, and the dispersion around the mean.

R^2 is between 0 and 1 and it basically describes how well the variation of one variable is explained by the other variable. For this thesis it means that if $R^2=1$ we can expect, that for every SPARTACUS value the compared data set value is the same. R^2 was calculated for precipitation and temperature in each subcatchment and each data set for the years 2003-2015, using the daily aggregation (Strelec et al. 2013).

Root mean squared error

The squared residuals between SPARTACUS and each data set are summed up, divided by the number of observations, and the root is then extracted. RMSE is a quality criterion and describes how well or bad the data set is correlated to SPARTACUS. If the RMSE is high, the accordance between SPARTACUS and the compared data set is low (Reusser et al. 2009).

Equation 3-4: RMSE (Reusser et al. 2009)

$$\boxed{\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum (O_i - S_i)^2}}$$

3.3 Frequency of meteorological events

In a next step, the frequency of defined events is counted in all data sets for every year, to compare the numbers. The events are specified by taking the following meteorological measurements in account, as found in various reports. According to meteorologists frost days mean that the minimum temperature on these days is lower than 0°C. On an ice day the maximum temperature is lower than 0°C. On summer days the maximum temperature is higher than 25°C and on hot days it is higher than 30°C. Dry days are days with a precipitation sum of equal or less than 0.1 millimetre. Days with high precipitation events have a precipitation of equal of greater than 20 millimetres (Kromp-Kolb, Formayer, and Clementschitsch 2007).

The analysed data in this thesis only provide the mean daily temperature. Therefore, the specification is shifted to find reasonable numbers in comparing days with extreme cold or warm temperature. For this comparison frost days are specified as days with a mean temperature lower than 0°C. Warm days are defined with a mean temperature higher than 13°C. For precipitation the number of dry days and days with high precipitation are counted, the specification being the same as found in the literature. To help understanding the result tables at first sight, the numbers are categorized by colour. Whereas blue means that the numbers of the defined events are smaller than in Spartacus, orange means that they are higher. Green numbers tell that the days found in Spartacus and the data set are the same. These tables can be found in the appendix.

The tables in chapter 4.2 present an evaluation of the complete tables in the appendix. In the column of “SPARTACUS” the mean values in days per year of the defined events from all years are listed. For INCA, COSMO-REA6 and E-OBS the bias in percentage for every event of every year and subcatchment is calculated. Afterwards the mean of all years is computed. Consequently, a value of 145% means that in an average year the days of the defined event in the data set are overestimated by 45% compared to SPARTACUS. Equally, a value of 95% means that the days of the defined events in an average year are underestimated by 5% compared to SPARTACUS. Relatively, the bias is 5%.

3.4 Calculations and Data Plots

In the next step the data are plotted against each other. Calculations are done before, in order to make comparisons possible. They are shortly explained in this chapter. Every plot shows all four data sets, so that discrepancies are visible.

3.4.1 Temperature

For the comparison of temperature between 2003 and 2015 the following plots are generated for every data set and every subcatchment. The used unit is °C.

Mean annual temperature

The temperature of every year is averaged for this plot. Consequently, temperature of every day is summarized and divided by the numbers of days of the corresponding year.

Mean monthly temperature

The mean temperature for every month over all years is summarized and divided by the numbers of years. For example, the temperature of every January between 2003 and 2015 is summarized and divided by 13. Furthermore, these plots show the mean annual temperature for every data set.

Boxplots of seasonal residuals in temperature

For every subcatchment the daily residuals between SPARTACUS and the three other data set are calculated and plotted as boxplots for every season over all years between 2003 and 2015. The box itself covers the interquartile range – which is the range between the first and the third quartile – and shows the median. The whiskers, which include 1.5 of the IQR (Interquartile range), are also displayed. To get a closer look on the distribution, the plots are zoomed in and the outliers are therefore not all presented by the plots (Strelec et al. 2013).

Every season is described by three months: winter by December, January and February; spring by March, April, May; summer by June, July, August and fall by September, October and November. The residuals are calculated by subtracting SPARTACUS from one of the data sets. For example, the formula for INCA is described by Equation 3-5.

Equation 3-5: Daily Residuals, Temperature

$$Daily\ Temperature\ (INCA) - Daily\ Temperature\ (SPARTACUS) = Daily\ Residue$$

Maps of Residuals, temperature

The average mean daily temperature in Austria between the years 2003 and 2015 is calculated for each data set. Similar to Equation 3-5 SPARTACUS is then subtracted from the different data sets to get the residuals of the mean daily temperature using ArcGIS. The maps are plotted and they all are displayed using the same classes, to make comparison possible on first sight.

3.4.2 Precipitation

For the comparison of precipitation between 2003 and 2015 the following plots are created. The used unit is millimetres.

Annual precipitation height:

The precipitation of each year between 2003 and 2015 is summarized.

Mean monthly precipitation height:

The precipitation for every month over all years is summarized and divided by the numbers of years. For example, the precipitation of every January between 2003 and 2015 is summarized and divided by 13. Furthermore, these plots show the mean annual precipitation height for every data set. Consequently, the precipitation height of all years divided by the number of years.

Sum of Precipitation over Time

The lines in these graphs are constantly rising, as they summarize the precipitation of every day, starting in 2003 up to 2015. Moreover, tables are created that present the precipitation sum of the 31.12.2015 after adding up the precipitation of all 13 years.

Boxplots of seasonal residuals in precipitation

As already described in chapter 3.4.1 for temperature, the boxplots of the residuals are calculated for precipitation in the very same way. Consequently, as an example the formula for INCA is described by Equation 3-6. With the daily residuals for all years, the boxplots are computed.

Equation 3-6: Daily Residuals, Precipitation

$$Daily\ Precipitation\ (INCA) - Daily\ Precipitation\ (SPARTACUS) = Daily\ Residue$$

Maps of Residuals, precipitation

The mean annual precipitation sum in Austria between the years 2003 and 2015 is calculated for each data set. Similar to Equation 3-6 SPARTACUS is then subtracted from the different data sets to get the residuals of the mean annual precipitation sum, using ArcGIS. The maps are plotted and they all are displayed using the same classes, to make comparison possible on first sight.

4. Comparison of data sets and analysis

The steps stated in chapter 3 make it possible to evaluate the variation and agreement of the data sets. Results are listed and explained in the following chapter. SPARTACUS is the data set that all others are compared to. Since SPARTACUS does not cover the German part of the Salzach, the comparison for the overall Salzach catchment (Burghausen) is excluded.

4.1 Summary of statistics on temporal data series

The results of the statistic calculations can be found in Table 4-1 to Table 4-6 and are explained in chapter 4.1.1 to 4.1.4.

4.1.1 Temperature – Salzach

As shown in Table 4-1 the mean is underestimated throughout all seasons by the data sets. Relatively seen the highest differences are predicted by INCA. The variation tends to get higher with a higher subcatchment area.

The standard deviation is nearly as high in winter as it is in summer, and much higher when looking on the annual period. With only small discrepancies between the standard deviation of the data sets, the agreement is very high.

The bias values tell that all data sets are underestimating throughout winter and summer, and consequently also during the all year period. With a higher subcatchment area the absolute bias gets higher as well. In summer larger discrepancies are displayed than in winter, with magnitudes up to 2.9°C. The best agreement according to the bias is found during the winter period in Sulzau. For temperature the relative bias is not significant, as problems occur when the temperature gets lower than 0°C, which is especially shown when looking on the results for the relative bias during winter.

R^2 is generally very high throughout all seasons, with values up to 0.99. E-OBS and COSMO-REA6 show a higher correlation in summer, while INCA has larger R^2 values in winter. The largest RMSE are calculated for INCA. The values span between 0.7 (E-OBS, Sulzau, summer) and 2.51 (INCA, Golling, summer). Throughout all seasons and catchments, the RMSE gets higher in summer and with an increasing catchment. Therefore, the biggest values are during summer time in Mittersill.

Table 4-1: Statistics of temperature in the Salzach catchment

Statistics	Subcatch-ment	Annual				Winter (DJF)				Summer (JJA)			
		SPARTA-CUS	INCA	COSMO-REA6	E-OBS	SPARTA-CUS	INCA	COSMO-REA6	E-OBS	SPARTA-CUS	INCA	COSMO-REA6	E-OBS
Mean [°C]	Sulzau	0.88	0.23	0.41	1.02	-6.88	-7.35	-6.89	-6.58	8.63	7.74	7.88	8.63
	Mittersill	3.39	2.41	2.46	2.40	-4.83	-5.45	-5.43	-5.48	11.37	10.10	10.50	10.20
	Golling	5.09	3.97	4.25	3.99	-3.59	-4.25	-4.15	-4.26	13.37	11.93	12.63	12.11
SD [°C]	Sulzau	7.38	7.28	7.10	7.11	4.73	4.67	4.77	4.25	3.91	4.00	3.58	3.72
	Mittersill	7.54	7.36	7.51	7.20	4.48	4.47	4.60	4.07	3.96	4.01	3.86	3.70
	Golling	7.69	7.44	7.75	7.30	4.27	4.16	4.35	3.89	3.91	3.94	4.00	3.52
relative bias [%]	Sulzau	-	-73.4	-54	16	-	-6.9	-0.1	4.2	-	-10.4	-8.7	-0.1
	Mittersill	-	-28.8	-27.3	-29.1	-	-12.8	-12.4	-13.4	-	-11.1	-7.6	-10.3
	Golling	-	-21.9	-16.3	-21.6	-	-18.4	-15.8	-18.9	-	-10.8	-5.6	-9.5
absolute bias [°C]	Sulzau	-	-0.65	-0.48	0.14	-	-0.47	-0.01	0.29	-	-0.90	-0.75	-0.01
	Mittersill	-	-0.98	-0.93	-0.98	-	-0.62	-0.60	-0.65	-	-1.26	-0.86	-1.17
	Golling	-	-1.11	-0.83	-1.10	-	-0.66	-0.57	-0.68	-	-1.44	-0.75	-1.26
R^2	Sulzau	-	0.92	0.97	0.99	-	0.79	0.89	0.96	-	0.77	0.95	0.97
	Mittersill	-	0.93	0.97	0.99	-	0.81	0.89	0.95	-	0.75	0.96	0.96
	Golling	-	0.93	0.98	0.98	-	0.81	0.89	0.90	-	0.74	0.96	0.96
RMSE	Sulzau	-	2.19	1.37	0.90	-	2.27	1.56	1.09	-	2.16	1.19	0.71
	Mittersill	-	2.28	1.55	1.37	-	2.11	1.65	1.25	-	2.42	1.19	1.41
	Golling	-	2.30	1.42	1.58	-	2.01	1.50	1.49	-	2.51	1.10	1.51

4.1.2 Temperature – Ybbs

While the mean values in INCA are always smaller than in SPARTACUS, for COSMO-REA6 and E-OBS the mean is only smaller in Greimpersdorf and bigger in Opponitz and Krenstetten as seen in Table 4-2. Relatively seen the differences are higher in winter, and the means in summer are matching well.

The standard deviation is generally higher in winter than it is in summer, and throughout the year it is logically higher than at any season. In E-OBS the smallest standard deviation is found compared to all other data sets.

Looking at the bias, an underestimation is predicted by INCA for all subcatchments, and by all data sets in Greimpersdorf. For INCA and E-OBS the bias for all catchments is smaller in winter, as it is in summer. While COSMO-REA6 shows the largest discrepancies in Opponitz, for INCA the highest divergence is in Greimpersdorf. For temperature the relative bias is not significant, as problems occur when the temperature gets lower than 0°C, which is especially shown when looking on the results for the relative bias during winter.

The RMSE is higher in INCA than it is in COSMO-REA6 and E-OBS. The lowest and therefore best RMSE value is 0.62 and can be found in E-OBS during summer. Generally, E-OBS has the smallest values in all catchments for all periods. The biggest RMSE are found in INCA for Greimpersdorf with values up to 2.65.

R^2 is between 0.7 and 0.99 in all catchments and seasons. The highest correlation is shown by E-OBS with values up to 0.99. While COSMO-REA6 and E-OBS show higher values of R^2 in summer, INCA has better results during winter. As the annual values for R^2 are higher compared to winter and summer, the conclusion can be drawn that the data sets are highly correlated during spring and fall.

Table 4-2: Statistics of temperature in the Ybbs catchment

Statistics	Subcatchment	Annual				Winter (DJF)				Summer (JJA)			
		SPARTACUS	INCA	COSMO-REA6	E-OBS	SPARTACUS	INCA	COSMO-REA6	E-OBS	SPARTACUS	INCA	COSMO-REA6	E-OBS
Mean [°C]	Opponitz	7.14	6.70	8.0	7.83	-2.03	-2.10	-0.93	-1.40	15.88	15.27	16.77	16.83
	Greimpersdorf	9.27	7.79	8.97	8.55	-0.29	-1.34	-0.50	-0.82	18.47	16.67	18.11	17.69
	Krenstetten	9.75	9.11	9.86	9.77	0.09	-0.42	-0.15	0.17	19.05	18.34	19.44	19.13
SD [°C]	Opponitz	7.94	7.79	8.20	7.91	4.38	4.19	4.62	4.12	3.57	3.85	4.39	3.43
	Greimpersdorf	8.18	7.93	8.38	7.80	4.36	4.15	4.42	4.12	3.52	3.71	4.27	3.40
	Krenstetten	8.26	8.19	8.68	8.16	4.40	4.33	4.53	4.22	3.51	3.63	4.11	3.36
relative bias [%]	Opponitz	-	-6.2	12.7	9.6	-	3.2	-54	-31	-	-3.9	5.6	6
	Greimpersdorf	-	-16	-3.3	-7.8	-	354.4	68.3	177.5	-	-9.8	-1.9	-4.2
	Krenstetten	-	-6.6	1.1	0.2	-	-581.3	-268.1	94.9	-	-3.7	0	0.4
absolute bias [°C]	Opponitz	-	-0.44	0.91	0.69	-	-0.07	1.01	0.63	-	-0.61	0.90	0.95
	Greimpersdorf	-	-1.50	-0.30	-0.72	-	-1.05	-0.20	-0.52	-	-1.80	-0.35	-0.77
	Krenstetten	-	-0.64	0.11	0.02	-	-0.51	-0.24	0.08	-	-0.71	0.39	0.08
R^2	Opponitz	-	0.93	0.96	0.97	-	0.78	0.82	0.88	-	0.71	0.93	0.95
	Greimpersdorf	-	0.94	0.97	0.99	-	0.79	0.84	0.94	-	0.73	0.91	0.96
	Krenstetten	-	0.94	0.98	0.99	-	0.76	0.91	0.96	-	0.75	0.90	0.97
RMSE	Opponitz	-	2.16	1.84	1.43	-	2.07	2.27	1.67	-	2.19	1.62	1.25
	Greimpersdorf	-	2.49	1.57	1.18	-	2.27	1.78	1.20	-	2.65	1.44	1.06
	Krenstetten	-	2.10	1.35	0.75	-	2.25	1.38	0.84	-	1.97	1.41	0.62

4.1.3 Precipitation – Salzach

In the Salzach catchment the mean daily precipitation sum is overestimated by all data sets, as seen in Table 4-4. Only E-OBS is underestimating the mean precipitation sum in summer. The means vary less, the bigger the catchments are. Whereas in winter the biggest differences can be found for E-OBS, in summer the largest discrepancies occur for INCA.

The standard deviation shows that the data are highest spread in Sulzau for all data sets and time periods. Moreover, it is greater in summer than it is in winter. In the Salzach catchment it is visible, that the bigger the catchment area, the smaller is the standard deviation. E-OBS shows a smaller standard deviation in summer and a bigger one in winter. The highest relative differences of the SD are found in E-OBS for the summer months.

All R^2 have a tendency of getting higher with an increasing catchment area. According to R^2 the best correlation is shown by E-OBS with values up to 0.89. The worst correlation is shown by INCA, with values for R^2 of less than 0.1. While E-OBS gets better results in summer, COSMO-REA6 and INCA achieve higher R^2 values during winter.

Table 4-3: R^2 of precipitation between INCA and SPARTACUS on a monthly basis – Salzach

Subcatchment	Sulzau	Mittersill	Golling
R^2	0.79	0.89	0.93

Looking at the RSME, E-OBS has the smallest RSME for all time periods and subcatchments. On the contrary, INCA has the highest results for RSME, meaning that the biggest variance can be found in INCA, with the RSME being more than twice as high as for E-OBS.

The relative and absolute bias show that all data sets tend to overestimate SPARTACUS apart from E-OBS during the summer period and COSMO-REA6 in Sulzau. The absolute bias gets up to nearly 2 mm in INCA during summer time. In winter the discrepancies for E-OBS are highest, with a relative bias of 50 %. While the relative and absolute bias present a better agreement of COSMO-REA6 and E-OBS in summer, INCA seems to work better during winter.

Table 4-4 Statistics of precipitation in the Salzach catchment

Statistics	Subcatch-ment	Annual				Winter (DJF)				Summer (JJA)			
		SPARTA-CUS	INCA	COSMO-REA6	E-OBS	SPARTA-CUS	INCA	COSMO-REA6	E-OBS	SPARTA-CUS	INCA	COSMO-REA6	E-OBS
Mean (mm)	Sulzau	4.37	5.19	4.91	4.66	2.85	3.27	3.91	4.08	6.55	8.43	6.49	5.61
	Mittersill	4.01	4.49	4.66	4.56	2.62	2.81	3.41	3.91	6.14	7.34	6.67	5.64
	Golling	3.95	4.30	4.62	4.61	2.77	3.06	3.59	3.74	5.94	6.50	6.49	5.80
SD (mm)	Sulzau	8.34	9.86	8.50	7.65	5.86	6.41	6.47	6.587	10.00	12.43	10.37	8.36
	Mittersill	7.39	8.32	7.95	7.58	5.01	5.55	5.71	6.37	9.15	10.43	10.02	8.51
	Golling	6.93	7.27	7.53	7.48	5.12	5.55	5.72	5.79	8.49	8.67	9.25	8.31
relative bias [%]	Sulzau	-	18.8	12.4	6.6	-	14.8	37.1	43.1	-	28.7	-0.9	-14.4
	Mittersill	-	12	16	13.7	-	7.3	30.1	49.2	-	19.6	8.6	-8.1
	Golling	-	8.7	17	16.6	-	10.4	29.8	35.3	-	9.4	9.3	-3.2
absolute bias [mm]	Sulzau	-	0.82	0.54	0.29	-	0.43	1.06	1.23	-	1.88	-0.06	-0.94
	Mittersill	-	0.48	0.64	0.55	-	0.19	0.79	1.29	-	1.20	0.53	-0.50
	Golling	-	0.34	0.67	0.65	-	-0.29	0.83	0.98	-	0.56	0.55	-0.19
R^2	Sulzau	-	0.01	0.46	0.67	-	0.02	0.52	0.65	-	0.00	0.39	0.70
	Mittersill	-	0.02	0.54	0.72	-	0.04	0.62	0.74	-	0.01	0.47	0.74
	Golling	-	0.03	0.61	0.76	-	0.05	0.64	0.70	-	0.01	0.54	0.78
RMSE	Sulzau	-	12.15	6.79	4.85	-	8.11	4.76	4.12	-	15.53	8.83	5.59
	Mittersill	-	10.24	5.63	4.15	-	6.72	3.66	3.50	-	13.26	7.66	4.76
	Golling	-	9.15	4.90	3.76	-	6.64	3.58	3.31	-	11.44	6.52	4.10

4.1.4 Precipitation – Ybbs

As shown by Table 4-6 in most of the time the mean is overestimated by INCA and underestimated by COSMO-REA6 and E-OBS. Only for Greimpersdorf, COSMO-REA6 overestimates and INCA shows an underestimation for Opponitz in winter. While INCA and E-OBS have smaller discrepancies in summer, COSMO-REA6 shows a higher accordance of the mean during winter for 2 subcatchments. The biggest differences for the mean can be found during the winter period for E-OBS.

The standard deviation is in general higher in summer than in winter and has also a better agreement in summertime. E-OBS shows a smaller SD in all catchments, and an especially low one in Opponitz. COSMO-REA6 has a bigger SD in Greimpersdorf and a smaller one in the other subcatchments. For INCA a higher SD is predicted in Greimpersdorf and Krenstetten and a slightly lower one in Opponitz.

With values under 0.1 R^2 tells that SPARTACUS does not explain the variation of INCA. For COSMO-REA6 the correlation in winter is slightly better than in summer with the best results of R^2 being 0.74 in Krenstetten. In summer E-OBS show the highest correlation compared to the other data sets, as R^2 gets up to 0.71. As the R^2 values on a monthly basis show such low results for INCA, they are again calculated on a monthly basis, resulting in much better values, with all of them being greater than 0.9 as shown in Table 4-5.

Table 4-5: R^2 of precipitation between INCA and SPARTACUS on a monthly basis – Ybbs

Subcatchment	Opponitz	Greimpersdorf	Krenstetten
R^2	0.91	0.92	0.91

According to the RMSE, E-OBS shows the smallest discrepancies compared to INCA and COSMO-REA6. INCA has the highest discrepancies with the RMSE being higher in summer than in winter. Discrepancies are lower for all data sets in Krenstetten, and during the winter period.

The relative bias tells that E-OBS underestimates SPARTACUS up to 65% during winter while INCA overestimates up to 35%. COSMO-REA6 underestimates in Opponitz and Krenstetten and overestimates in Greimpersdorf. The bias is smaller in summer than it is in winter. In INCA the highest absolute bias can be found to be 1.11 mm.

Table 4-6: Statistics of precipitation in the Ybbs catchment

Statistics	Subcatchment	Annual				Winter (DJF)				Summer (JJA)			
		SPAR-TA-CUS	INCA	COSMO-REA6	E-OBS	SPARTA-CUS	INCA	COSMO-REA6	E-OBS	SPARTA-CUS	INCA	COSMO-REA6	E-OBS
Mean (mm)	Opponitz	4.75	4.89	4.43	2.50	4.43	4.18	4.13	1.56	6.15	6.53	5.54	3.87
	Greimpersdorf	3.12	4.03	3.49	2.39	2.45	3.32	3.08	1.49	4.34	5.45	4.54	3.71
	Krenstetten	2.80	3.24	2.43	2.22	2.09	2.47	1.94	1.40	3.99	4.57	3.31	3.44
SD (mm)	Opponitz	9.43	9.30	8.40	4.90	8.32	8.00	6.62	2.89	11.31	10.83	10.40	6.36
	Greimpersdorf	6.56	7.75	6.71	4.68	4.66	6.28	4.92	2.73	8.33	9.14	8.45	6.08
	Krenstetten	6.00	6.63	5.37	4.47	4.03	4.76	3.38	2.61	7.84	8.25	7.11	5.82
relative bias [%]	Opponitz	-	2.8	-6.8	-47.4	-	-5.5	-6.8	-64.8	-	6.3	-10	-37.1
	Greimpersdorf	-	29.1	11.8	-23.4	-	35.5	25.5	-39.2	-	25.6	4.6	-14.6
	Krenstetten	-	15.8	-13.3	-20.9	-	18.1	-7.1	-33.4	-	14.6	0	-13.9
absolute bias [mm]	Opponitz	-	0.14	-0.33	-2.26	-	-0.25	-0.30	-2.87	-	0.39	-0.61	-2.28
	Greimpersdorf	-	0.91	0.37	-0.73	-	0.87	0.63	-0.96	-	1.11	0.20	-0.63
	Krenstetten	-	0.44	-0.37	-0.59	-	0.38	-0.15	-0.70	-	0.58	-0.68	-0.55
R^2	Opponitz	-	0.06	0.63	0.53	-	0.07	0.68	0.48	-	0.04	0.56	0.57
	Greimpersdorf	-	0.05	0.60	0.66	-	0.05	0.65	0.65	-	0.05	0.50	0.65
	Krenstetten	-	0.04	0.53	0.74	-	0.04	0.60	0.78	-	0.04	0.42	0.71
RMSE	Opponitz	-	11.48	5.84	7.13	-	9.83	4.70	7.25	-	14.00	7.82	8.04
	Greimpersdorf	-	9.01	4.47	3.94	-	7.03	3.04	3.10	-	11.00	6.39	5.03
	Krenstetten	-	8.04	4.25	3.17	-	5.62	2.57	2.22	-	10.22	6.35	4.35

4.2 Frequency of meteorological events

This chapter lists the results of the frequency analysis of meteorological events. A complete table of all subcatchments and years can be found in chapter 10.1 to chapter 10.4. Table 4-7 explains again the defined events.

Table 4-7: Definition of defined events

Frost Days	mean daily temperature <= 0°C
Warm Days	mean daily temperature >= 13°C
Dry Days	mean daily precipitation <= 0.1mm
Wet Days	mean daily precipitation >= 20mm

4.2.1 Salzach

The results for the Salzach catchment are divided into temperature and precipitation. A cutout of the complete tables is presented in Table 4-8. Table 10-1 and Table 10-2 show the numbers of defined events in the Salzach catchment, for each year and each subcatchment.

Table 4-8:Cutout of defined events in the Salzach catchment

Subcatchment	Frost days (Tmean<=0°C)				Warm Days (Tmean>=13°C)			
	SPAR-TACUS	INCA	COSMO-REA6	E-OBS	SPAR-TACUS	INCA	COSMO-REA6	E-OBS
Sulzau, 2003	174	184	181	162	23	15	14	32
Sulzau, 2004	162	179	178	158	2	0	0	2
Sulzau, 2005	155	170	169	149	7	3	2	12
Sulzau, 2006	153	168	171	152	11	7	3	14
Sulzau, 2007	160	173	178	159	9	7	5	9
Sulzau, 2008	181	186	185	181	3	0	0	2
Sulzau, 2009	160	168	167	156	9	5	2	6
Sulzau, 2010	176	185	186	173	17	13	5	14
Sulzau, 2011	138	160	152	139	11	10	11	10
Sulzau, 2012	156	158	169	160	15	13	10	10
Sulzau, 2013	174	184	172	174	18	14	11	14
Sulzau, 2014	135	139	145	145	6	4	1	3
Sulzau, 2015	144	162	157	150	29	22	20	24
Mittersill, 2003	138	150	153	144	65	45	51	54
Mittersill, 2004	135	149	146	140	31	18	20	21
Mittersill, 2005	131	139	137	132	29	20	19	25
Mittersill, 2006	123	132	135	132	47	31	33	35

Temperature

In the Salzach catchment the frost days are overestimated by all three data sets compared to SPARTACUS. Table 4-9 shows that E-OBS has the best agreement with SPARTACUS. However, a closer look at the tables in the appendix shows, that E-OBS is underestimating frost days in Sulzau from 2003-2010 and overestimating from 2010-2015. In two years (2008, 2013) E-OBS and SPARTACUS have the same number of frost days.

Warm days are underestimated by more than 30% in INCA and COSMO-REA6. Similar to frost days, E-OBS overestimates the numbers in the first years. E-OBS has the same numbers as SPARTACUS for 2004 and 2007.

Table 4-9: Mean bias [%] between SPARTACUS and data sets for defined events of temperature in the Salzach catchment

Subcatchment	Frost Days (Tmean<=0°C)				Warm Days (Tmean>=13°C)			
	SPARTACUS [days]	INCA [%]	COSMO-REA6 [%]	E-OBS [%]	SPARTACUS [days]	INCA [%]	COSMO-REA6 [%]	E-OBS [%]
Sulzau	159	107	107	100	12	60	41	94
Mittersill	124	111	112	112	39	65	71	61
Golling	102	116	116	117	63	69	82	68

Precipitation

Table 4-10 indicates that dry days are underestimated by INCA and COSMO-REA6, with the highest bias showing in Mittersill. Whereas COSMO-REA6 is constantly underestimating SPARTACUS over all years, INCA overestimates SPARTACUS one third of the time. For example, in 2009, 2010, 2014 and 2015 INCA has more dry days as SPARTACUS in Sulzau, Mittersill and Golling. INCA shows the lowest difference to SPARTACUS.

Looking at the days with a high precipitation, the numbers are overestimated by E-OBS, particularly high in Golling. For five years in Sulzau, E-OBS has a smaller number of dry days than SPARTACUS. E-OBS has mostly greater numbers of days with high precipitation for Mittersill, Golling and mostly smaller numbers for Sulzau.

Table 4-10: Mean bias [%] between SPARTACUS and data sets for defined events of precipitation in the Salzach catchment

Subcatch-ment	Dry Days (P<=0.1mm/day)				Days with High Precipitation (P>=20mm/day)			
	SPAR-TACUS [days]	INCA [%]	COSMO-REA6 [%]	E-OBS [%]	SPAR-TACUS [days]	INCA [%]	COSMO-REA6 [%]	E-OBS [%]
Sulzau	154	98	87	103	21	129	109	87
Mittersill	155	97	83	107	16	126	125	109
Golling	132	97	88	117	15	110	119	121

4.2.2 Ybbs

The results for the Ybbs catchment are divided into temperature and precipitation. The results for the Ybbs catchment are divided into temperature and precipitation. A cutout of the complete tables is presented in Table 4-11. Table 10-3 and Table 10-4 show the numbers of defined events in the Ybbs catchment, for each year and each subcatchment.

Table 4-11: Cutout of defined events in the Ybbs catchment

Subcatchment	Dry Days (P<=0.1mm/day)				Days with High Precipitation (P>=20mm/day)			
	SPAR-TACUS	INCA	COSMO-REA6	E-OBS	SPAR-TACUS	INCA	COSMO-REA6	E-OBS
Opponitz, 2003	183	173	176	231	13	11	10	4
Opponitz, 2004	144	143	149	199	17	18	13	3
Opponitz, 2005	138	144	141	195	29	29	21	6
Opponitz, 2006	151	147	131	204	26	23	22	5
Opponitz, 2007	146	135	142	196	23	17	24	7
Opponitz, 2008	151	152	144	188	24	23	24	4
Opponitz, 2009	135	136	120	179	32	32	35	11
Opponitz, 2010	127	131	130	192	21	18	17	7
Opponitz, 2011	179	164	178	223	22	20	12	6
Opponitz, 2012	150	143	140	192	19	22	27	3
Opponitz, 2013	139	103	147	189	27	34	21	5
Opponitz, 2014	152	143	149	180	17	26	21	9
Opponitz, 2015	169	170	160	221	18	13	13	5

Temperature

Regarding frost days Table 4-12 presents that while INCA overestimates SPARTACUS in all Ybbs subcatchments COSMO-REA6 and E-OBS underestimate the frost days in Opponitz and overestimate them in Greimpersdorf and Krenstetten. INCA has a small bias in Opponitz, which raises in Krenstetten and is highest in Greimpersdorf. For COSMO-REA6 and E-OBS the highest mean bias for frost days in all subcatchments is 16%, whereas for INCA it is 30%.

Warm days are underestimated by INCA, with the highest bias in Greimpersdorf. COSMO-REA6 slightly underestimates Greimpersdorf, and overestimates Opponitz and Krenstetten. E-OBS has higher numbers of warm days for Opponitz over all years and around one third of the years from Krenstetten. All other years from Krenstetten and all years from Opponitz are overestimated. The highest mean difference in COSMO-REA6 and E-OBS can be found for Opponitz and is around 13%.

Table 4-12: Mean bias [%] between SPARTACUS and data sets for defined events of temperature in the Ybbs catchment

Subcatchment	Frost days (Tmean<=0°C)				Warm Days (Tmean>=13°C)			
	SPARTACUS [days]	INCA [%]	COSMO-REA6 [%]	E-OBS [%]	SPARTACUS [days]	INCA [%]	COSMO-REA6 [%]	E-OBS [%]
Opponitz	76	107	88	85	99	88	113	112
Greimpersdorf	53	130	116	109	138	79	94	90
Krenstetten	49	113	109	94	145	92	103	99

Precipitation

As shown in Table 4-13 INCA has a smaller and E-OBS a higher number of dry days for the whole Ybbs catchment as SPARTACUS. COSMO-REA6 underestimates in Greimpersdorf, the majority of the years in Opponitz and half of the years in Krenstetten. The remaining years are overestimated. Therefore, the mean bias in Table 4-13 is misleadingly very high.

For the days with a precipitation higher as 20mm/day, INCA very highly – up to 50% in Greimpersdorf – overestimates nearly all years in Greimpersdorf and Krenstetten. Only in Opponitz half of the years have smaller number than in SPARTACUS. However, in Opponitz the bias is very small, sometimes even being zero. All numbers in E-OBS are smaller than in SPARTACUS and they differ very highly, up to more than 70%. In general, there are nearly as many numbers in COSMO-REA6 that are higher than SPARTACUS as there are numbers that are smaller. Most of the years in Greimpersdorf are overestimated whereas the majority of years for Opponitz and Krenstetten are underestimated.

Table 4-13: Mean bias [%] between SPARTACUS and data sets for defined events of precipitation in the Ybbs catchment

Subcatchment	Dry Days (P<=0.1mm/day)				Days with High Precipitation (P>=20mm/day)			
	SPARTACUS [days]	INCA [%]	COSMO-REA6 [%]	E-OBS [%]	SPARTACUS [days]	INCA [%]	COSMO-REA6 [%]	E-OBS [%]
Opponitz	151	96	97	132	22	99	90	27
Greimpersdorf	168	86	88	114	11	150	115	54
Krenstetten	173	88	98	114	9	135	84	53

4.3 Data Plots – Temperature

The following subchapters describes the results found in the graphs which have already been described in chapter 3. All graphs can be found in the appendix, with some example plots being shown in this chapter as well to get an impression and to show the most important ones. Again, SPARTACUS is the reference data set and therefore used to compare to.

4.3.1 Mean monthly temperature

The plots for the mean monthly temperature are assessed, looking separately on the different catchments, as shown in Figure 4-1.

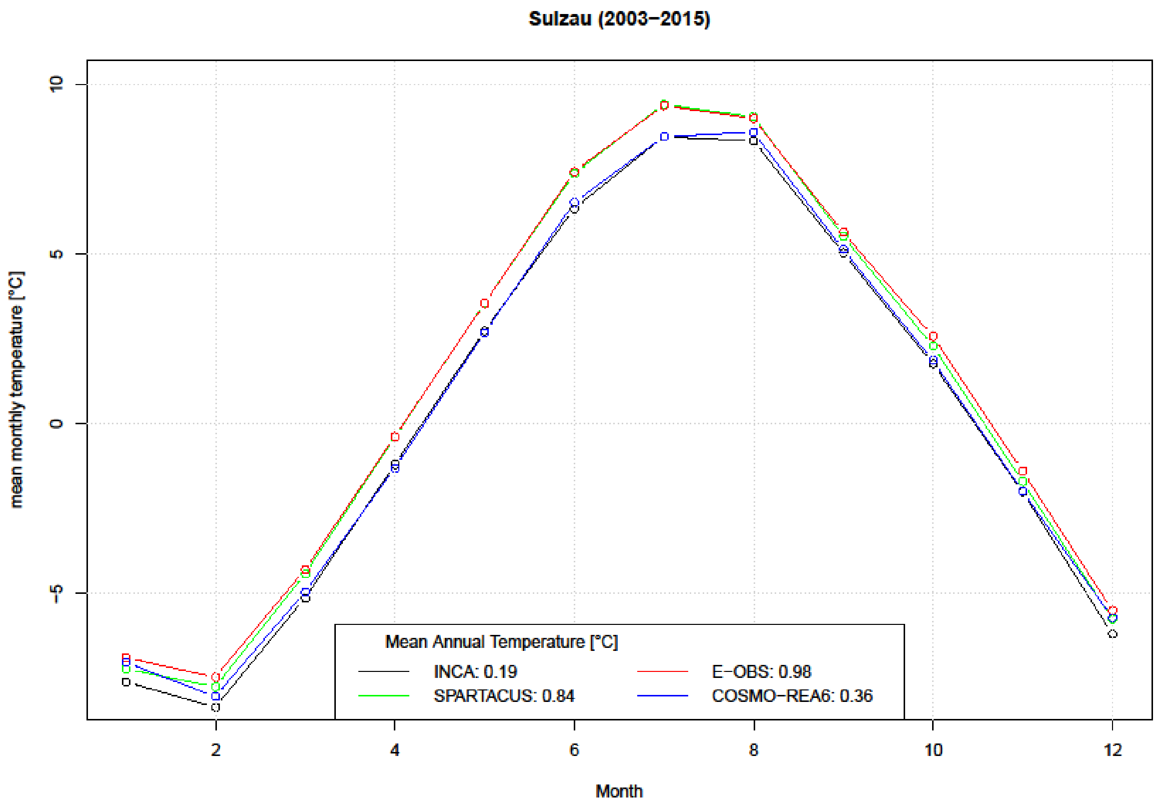

Figure 4-1: Mean monthly temperature – Sulzau

Salzach

Figure 10-1 to Figure 10-3 show the mean monthly temperature in the Salzach catchment. A reasonable consistent interannual variability of the mean monthly temperature is shown by all data sets. The only difference is displayed in February. Whereas SPARTACUS has a rising temperature from January to February in Golling, it is found decreasing in all other data sets for the whole Salzach catchment.

In the Salzach subcatchments the mean annual temperature is underestimated by all data sets compared to SPARTACUS. Only in Sulzau, E-OBS slightly overestimates the temperature as shown in Figure 4-1. The bias between SPARTACUS and the other data sets is almost 1°C in Mittersill (Figure 4-2) and Golling. Among all data sets INCA has the largest differences to SPARTACUS and shows therefore the lowest mean annual temperature and the lowest mean monthly temperature throughout nearly all months.

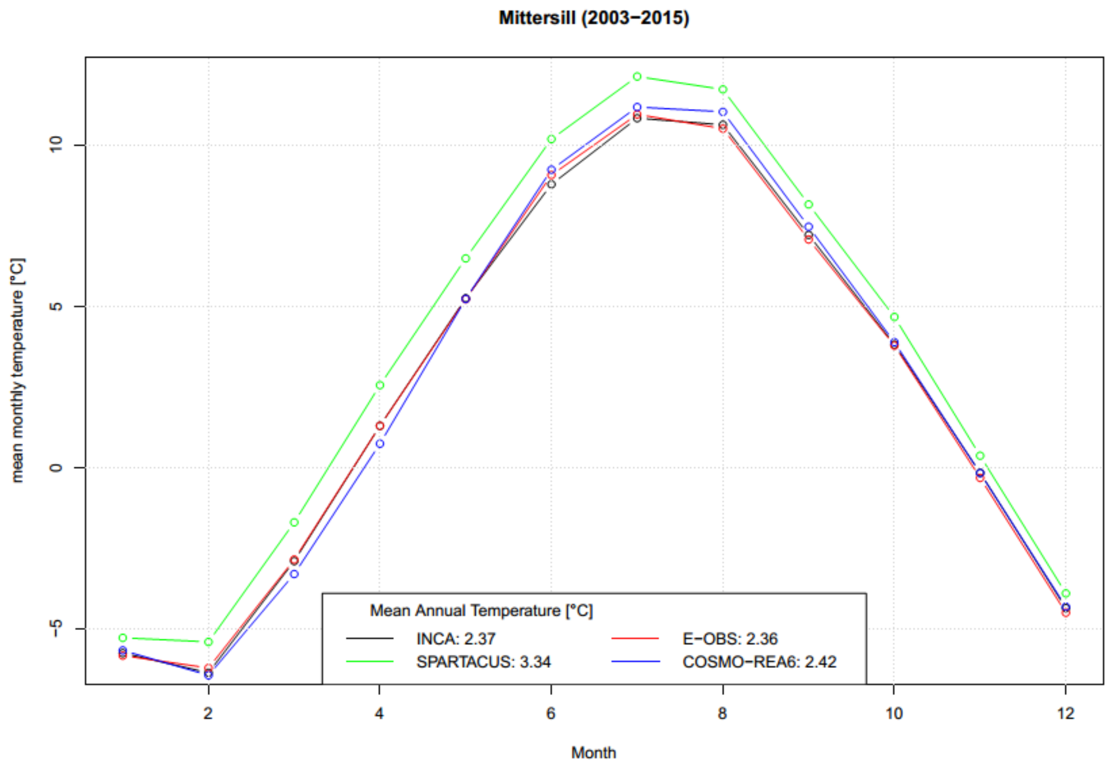

Figure 4-2: Mean monthly temperature – Mittersill

For Mittersill and Golling the data sets INCA, E-OBS and COSMO-REA6 have a higher agreement to each other than they have to SPARTACUS. It appears that the bias for all data sets is slightly higher in summer. The mean annual temperature span from Sulzau to Golling the following values: 0.19°C – 3.93°C (INCA), 0.84°C – 5.04°C (SPARTACUS), 0.98°C – 3.94°C (E-OBS), 0.36°C – 4.21°C (COSMO-REAG6).

Ybbs

Figure 10-4 to Figure 10-6 show the mean monthly temperature in the Ybbs catchment. While COSMO-REA6 and E-OBS are overestimating the mean annual and mean monthly temperature in Opponitz (Figure 4-3) and Krenstetten, SPARTACUS is underestimated by them in Greimpersdorf. COSMO-REA6 and E-OBS have a high agreement, with a maximum shift of 0.5°C to each other. INCA has constantly smaller temperature values than SPARTACUS, with differences up to 2°C. Furthermore, it has the lowest mean annual temperature in all subcatchments.

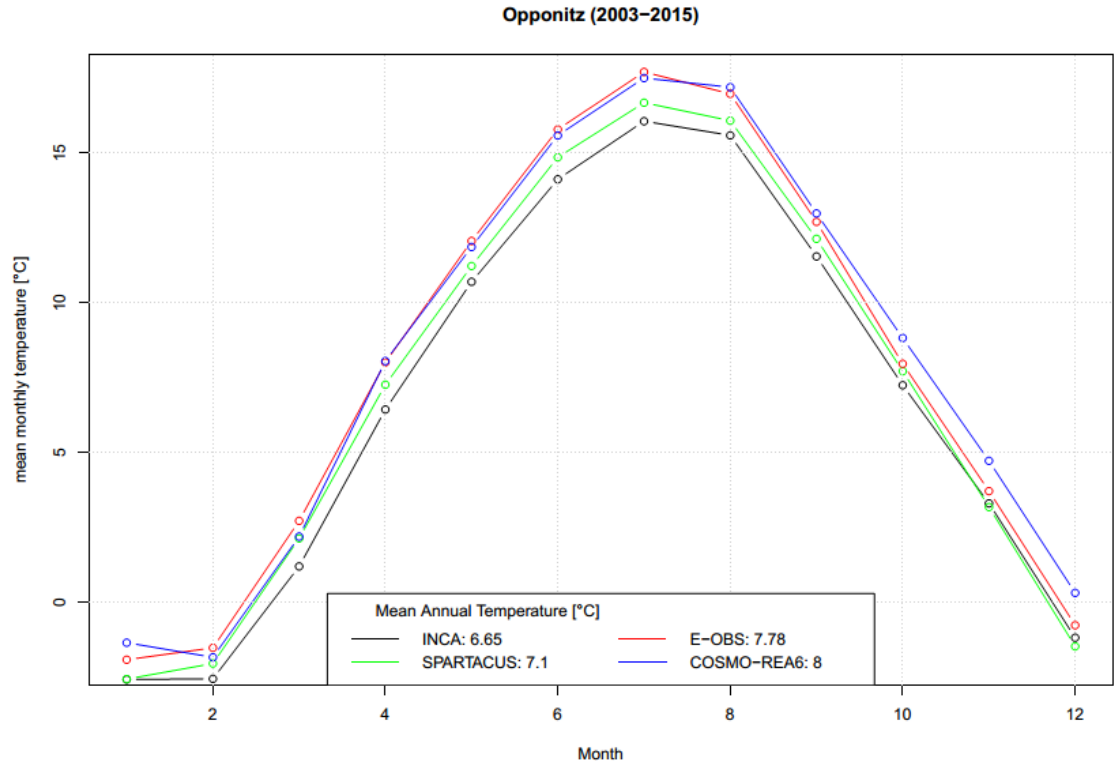

Figure 4-3: Mean monthly temperature – Opponitz

The interannual variability among the data sets matches well, with only having disagreements in the trends between January and February. For Krenstetten the data sets have the lowest differences. As determined for Salzach as well, the bias between the data sets is higher in summer. The mean annual temperature from Opponitz to Greimpersdorf the following values: 6.65°C – 9.06°C (INCA), 7.1°C – 9.71°C (SPARTACUS), 7.78°C – 9.72°C (E-OBS), 8.00°C – 9.81°C (COSMO-REAG6).

4.3.2 Mean annual temperature

The mean annual temperature for each subcatchment, as found in Figure 4-4, is compared looking on the different catchments and the different data sets.

Salzach

Figure 10-7 to Figure 10-9 present the mean annual temperature in the Salzach catchment. The annual variability of the mean annual temperature in Salzach are fairly well captured by E-OBS, COSMO-REA6 and INCA compared to SPARTACUS, although they are biased. All data sets demonstrate a tendency to underestimate SPARTACUS. Only E-OBS in Sulzau has a higher mean annual temperature than SPARTACUS.

In Mittersill and Golling (Figure 4-4) E-OBS, COSMO-REA6 and INCA have a higher agreement to each other than to SPARTACUS, with the bias being around 1°C. The bias is slightly higher in Sulzau, with E-OBS overestimating SPARTACUS. In the first few years INCA has the smallest mean annual temperature, and in the last few years E-OBS has the lowest values.

Figure 4-4: Mean annual temperature – Golling

Ybbs

Figure 10-10 to Figure 10-12 display the mean annual temperature in the Ybbs catchment. INCA has the biggest underestimation compared to SPARTACUS. Whereas SPARTACUS has the highest mean annual temperature in Greimpersdorf, it has the second lowest for Opponitz. The agreement between E-OBS and COSMO-REA6 is very high, with a bias smaller than 0.5°C. For Ybbs the discrepancy is highest in Greimpersdorf (Figure 4-5) between SPARTACUS und INCA and is around 1.5°C.

Figure 4-5: Mean annual temperature – Greimpersdorf

The trends between the years are similar in all data sets, and the under- or overestimations from SPARTACUS tend to be smaller than in the Salzach region. While in Greimpersdorf a significant higher bias between SPARTACUS and the other data sets can be found, the agreement among the data sets is best in Krenstetten as shown in Figure 4-6.

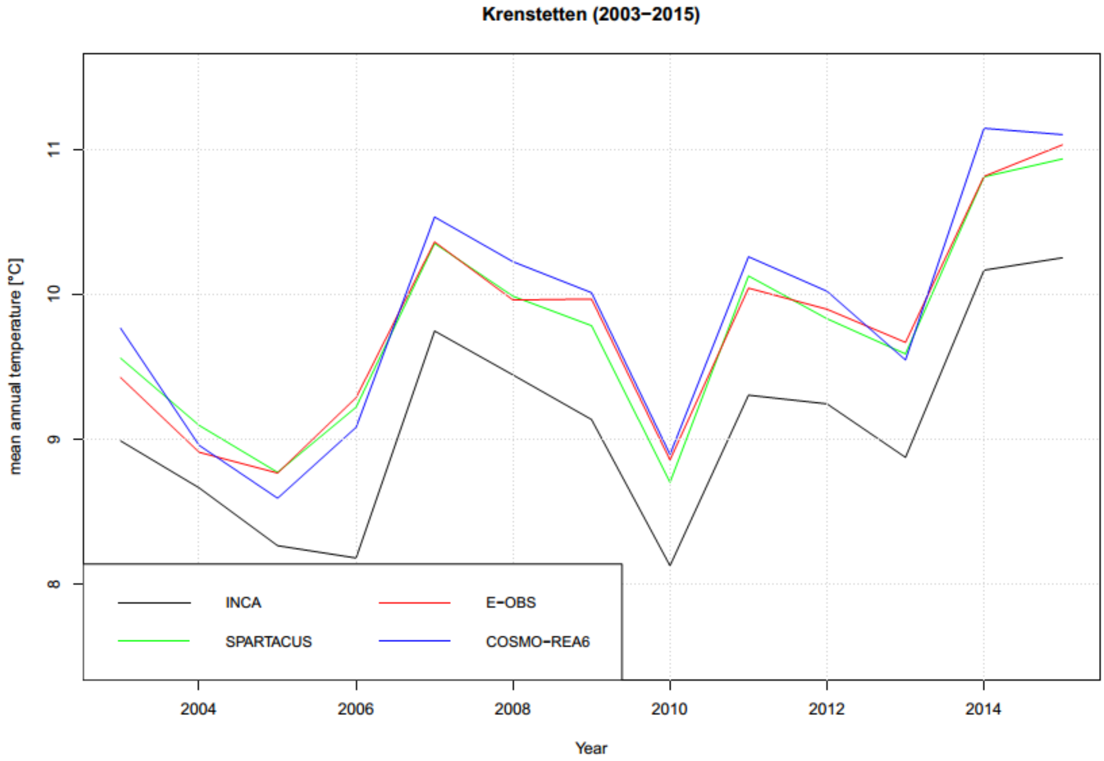

Figure 4-6: Mean annual temperature – Krenstetten

4.3.3 Boxplots of seasonal residuals in temperature

This chapter compares the boxplots of the seasonal residuals in temperature that can be found in the appendix, with an example found in Figure 4-10. For both, Salzach and Ybbs, an overview of the data is given and then each data set is assessed separately, using the information provided by the boxplots.

4.3.3.1 Salzach

Figure 10-31 to Figure 10-33 show the seasonal residuals in temperature in the Salzach catchment. In all boxplots, INCA has a wider range in the residuals than the other data sets and E-OBS predicts the smallest variation of residuals. While the interquartile range of INCA has values up to 3°C, for E-OBS the IQR values are only half as large as for INCA.

The majority of all three data sets obviously underestimates SPARTACUS in Mittersill and Golling, however the residuals show that an overestimation can be found for some seasons in Sulzau.

COSMO-REA6

In Sulzau the median of COSMO-REA6 shows an underestimation in spring, fall and summer and it is around 0 in winter. The highest bias of the medians for COSMO-REA6 is found in spring for all subcatchments. While in Mittersill underestimations of 0.3°C to 1.5°C is presented by the median values, it is around 0.75°C to 1.7°C in Golling (Figure 4-7).

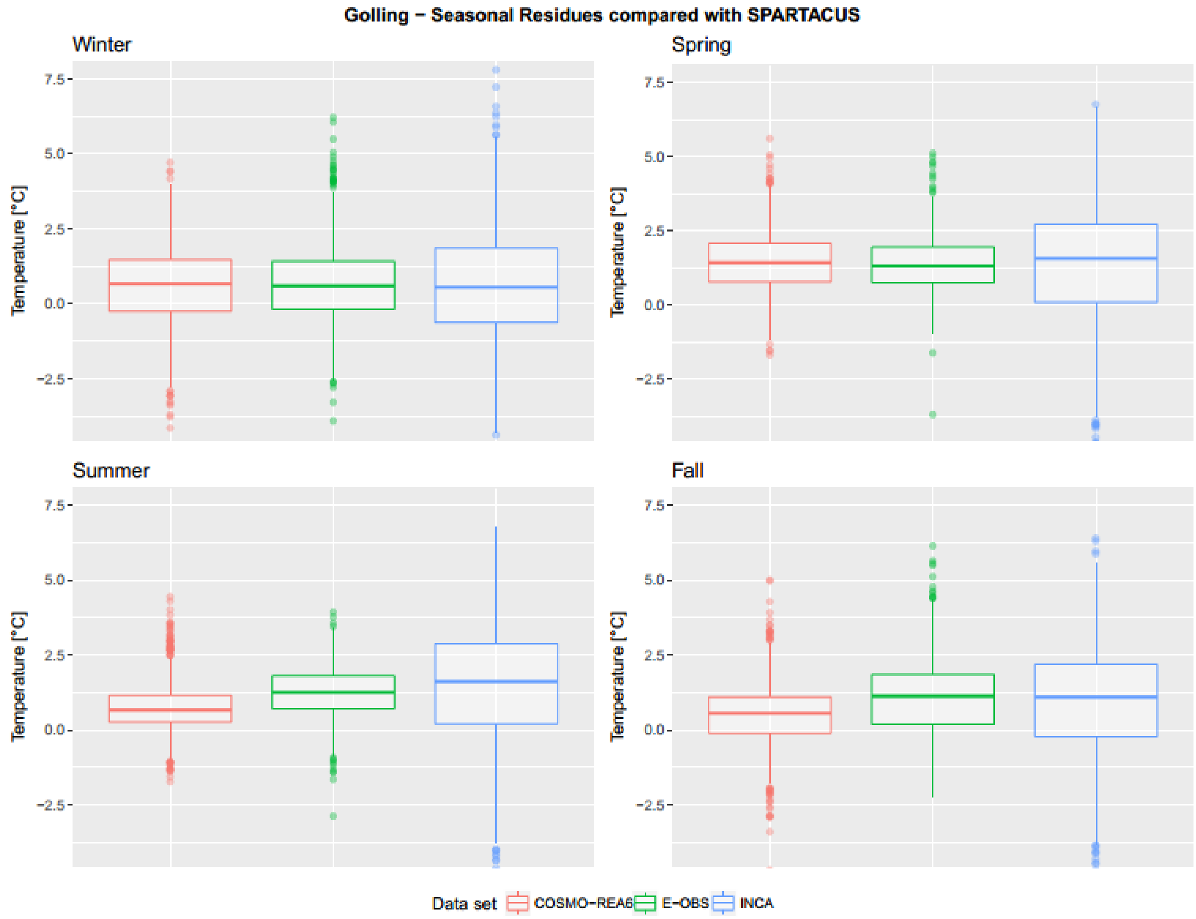

Figure 4-7: Seasonal residuals of temperature – Golling

However, more than 25% of the residuals show an overestimation during winter in Golling. In summer the IQR is smaller compared to the other seasons. The highest inter-quartile ranges are found in winter, meaning that the residuals are more scattered in this season.

E-OBS

While in Sulzau the highest bias in the medians can be found during winter with only 0.5°C, the bias between the medians is smallest during winter in Mittersill and Golling with around -0.5°C. During summer in Sulzau the median is closest to 0°C (Figure 4-8), however in Mittersill and Golling the medians in summer have the largest values with -1.2°C in Mittersill and -1.5°C in Golling (Figure 4-7). In all subcatchments the tendency of the variation for the E-OBS residuals shows, that the IQR is highest in winter and lowest in summer. The majority of the boxplots predict that most of the time far more than 75% of the residuals are negative, showing an underestimation. However, during winter in Golling, and all seasons in Sulzau, more than 50% of the residuals are positive, explaining an overestimation of the data (Figure 4-7 and Figure 4-8).

INCA

For all seasons the median of the residuals shows an underestimation with a bias between 0.3°C (Sulzau, Figure 4-8) and 1.5°C (Mittersill). Looking at the differences of the medians, depending on the season, they are closer to 0°C during winter than during summer, where the largest bias is found. In all subcatchments the difference of the median to 0°C is smaller in winter and fall, and bigger in summer and spring. The IQR displays that the data are highly spread. Among all boxplots, the smallest interquartile range is still 2°C. The whiskers and outliers also show a much higher spread than the residuals of COSMO-REA6 and E-OBS.

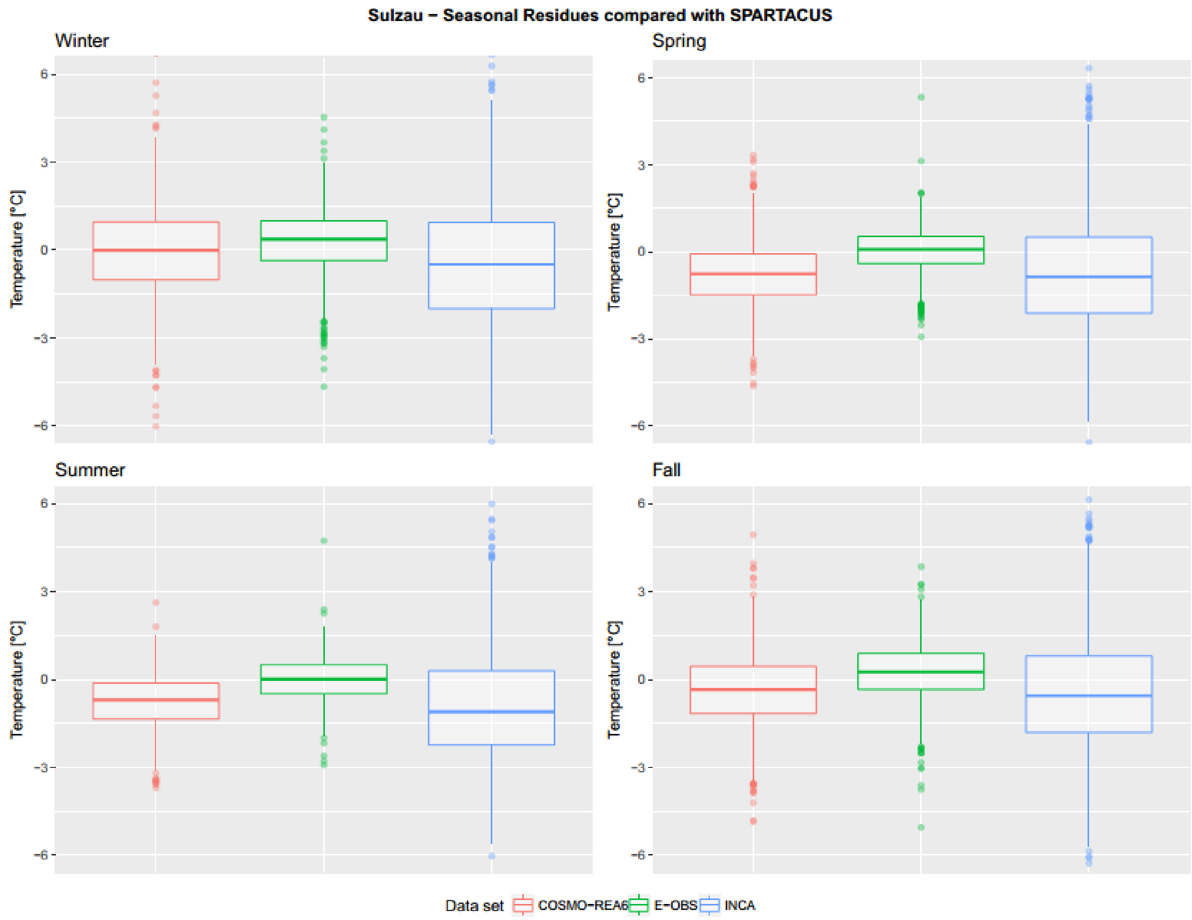

Figure 4-8: Seasonal residuals of temperature – Sulzau

In Sulzau (Figure 4-8) more than 25% of the data show an overestimation throughout all seasons, and in Mittersill and Golling an overestimation of more than 25% of the data are shown in winter and fall. The middle 50% of the residuals are underestimating SPARTACUS in all other catchments and seasons.

4.3.3.2 Ybbs

Figure 10-34 to Figure 10-36 represent the seasonal residuals in temperature in the Ybbs catchment. Similar as in Salzach, the residuals of INCA have a higher variation than those of the other data sets. The smallest variation is shown by E-OBS, where the boxplots are balanced around 0°C. In Opponitz the majority of the residuals of COSMO-REA6 and E-OBS show an overestimation, while for INCA a bigger part of the residuals presents an underestimation. (Figure 4-9)

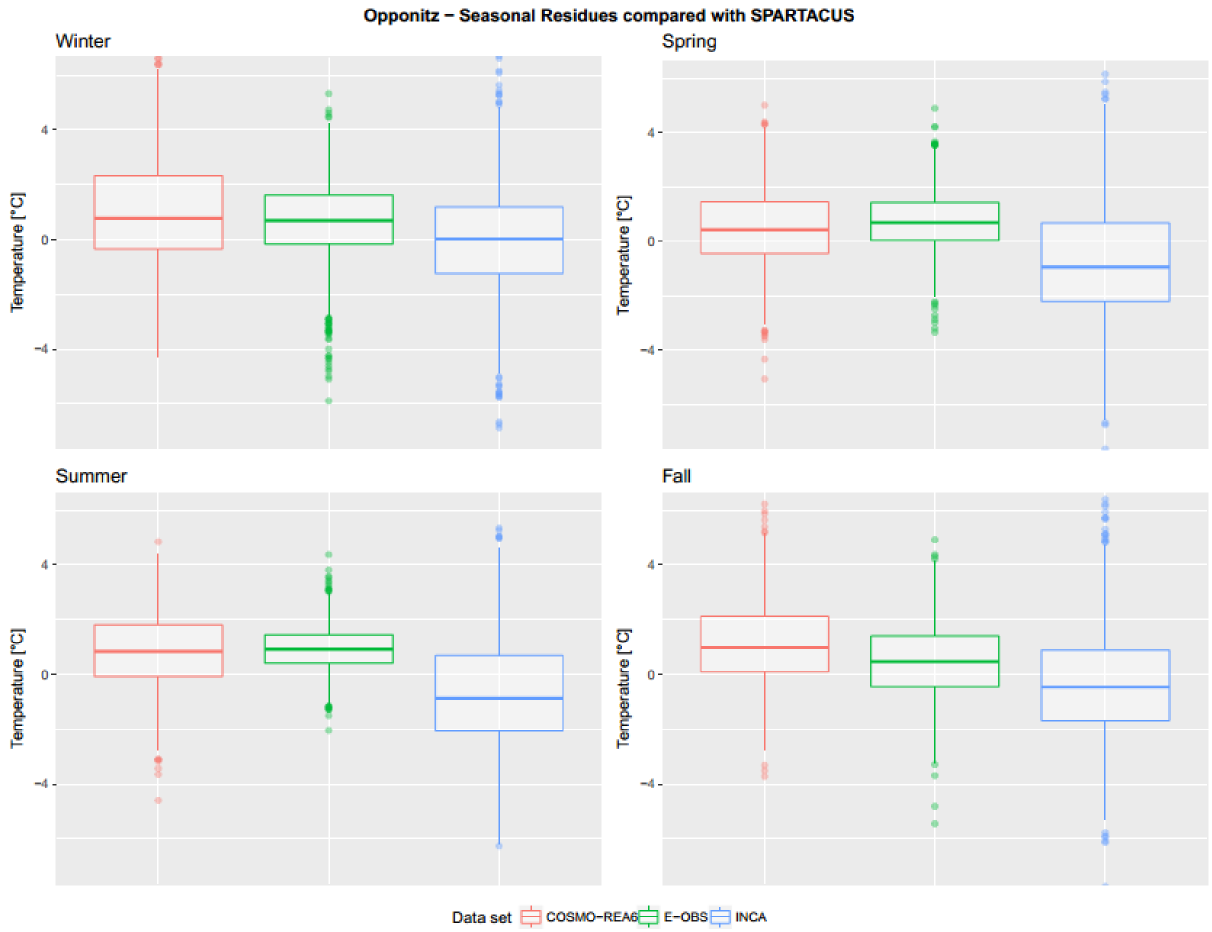

Figure 4-9: Seasonal residuals of temperature – Opponitz

In Greimpersdorf the median of all data sets is smaller than 0°C, with the highest difference in the INCA data set, where the median of the residuals predicts an underestimation of nearly 2.5°C during spring. E-OBS shows the best results for Krenstetten, where the median is always located around 0°C and the IQR is less than 1°C.

While the medians of the residuals in INCA predict a tendency of underestimating during all seasons in the Ybbs catchment, E-OBS is overestimating in Opponitz and underestimating in Greimpersdorf, and COSMO-REA6 is underestimating in Greimpersdorf (Figure 4-11) and overestimating in Opponitz.

COSMO-REA6

The median in Opponitz is around 1°C for all seasons. In Greimpersdorf and Opponitz the IQR is higher in winter with maximum values of 3°C, the minimum values of the IQR are 2°C. Also, in these two catchments the highest difference of the median is found to be -0.75°C and it is displayed during spring. The median is closest to 0°C during fall in Greimpersdorf. While COSMO-REA6 is mainly underestimating in Greimpersdorf and overestimating in Opponitz, the residuals in Krenstetten are balanced around 0°C for all seasons (Figure 4-10).

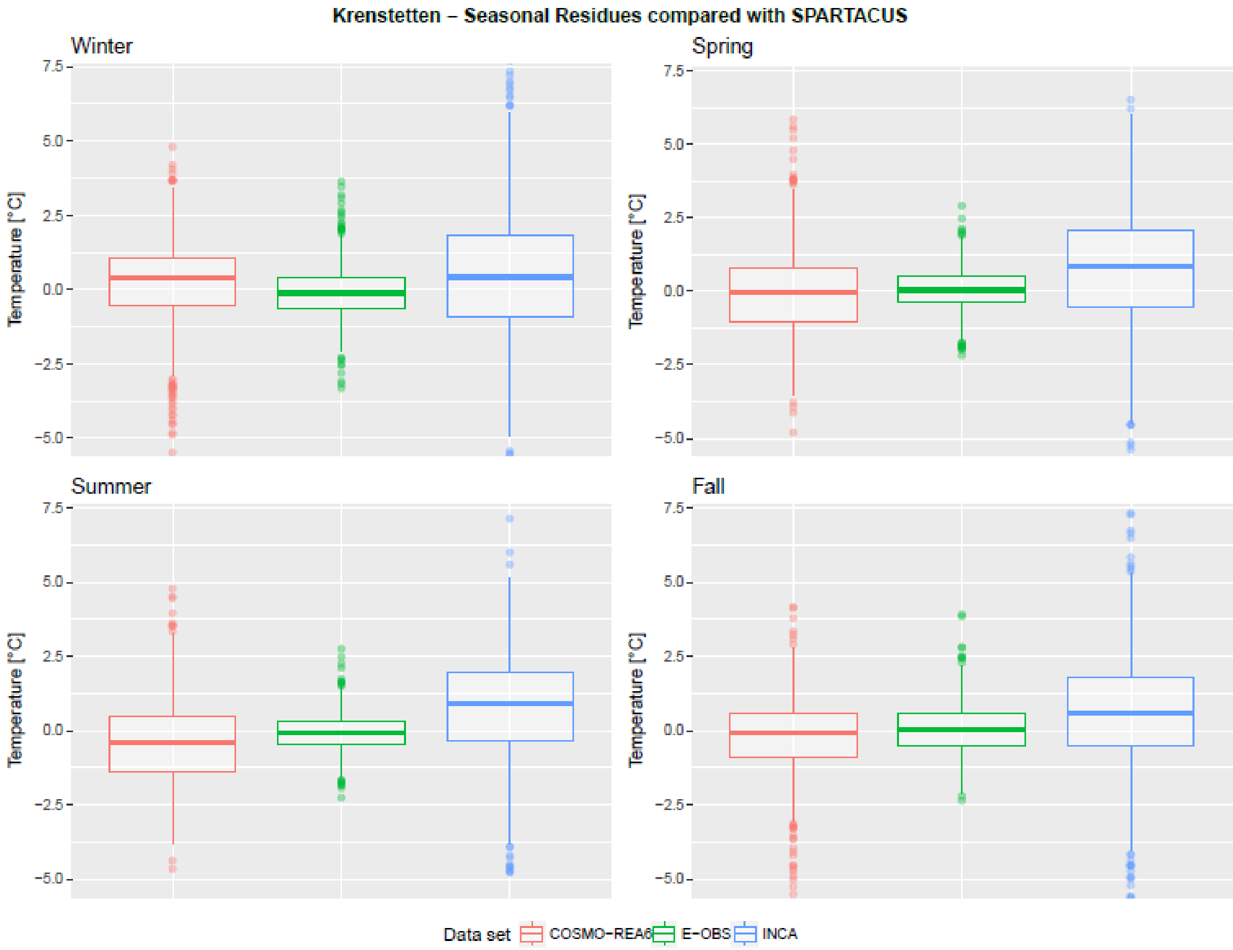

Figure 4-10: Seasonal residuals of temperature – Krenstetten

E-OBS

As explained, the E-OBS data show the smallest variation of the residuals. In Opponitz and Greimpersdorf the highest IQR is shown in winter and fall with values up to 2°C. (Opponitz, Figure 4-9) and 1.25°C (Greimpersdorf, Figure 4-11). The IQR in Krenstetten is similar in all seasons and has maximum values of 1°C. (Figure 4-10) With a range of the seasonal residuals around 5°C, the smallest distribution of differences is found in Greimpersdorf. In Opponitz slightly more than 25% are underestimating during winter and fall while during the other seasons more than 75% are overestimating. In Greimpersdorf it is the other way around, as 25% during winter and fall are overestimating, while during spring and summer more than 75% of the data show an underestimation (Figure 4-11).

INCA

The median in Opponitz is 0°C during winter, while it is between -0.5°C and -2°C in all other subcatchments and seasons, with the highest bias shown in Greimpersdorf during spring and summer (Figure 4-11).

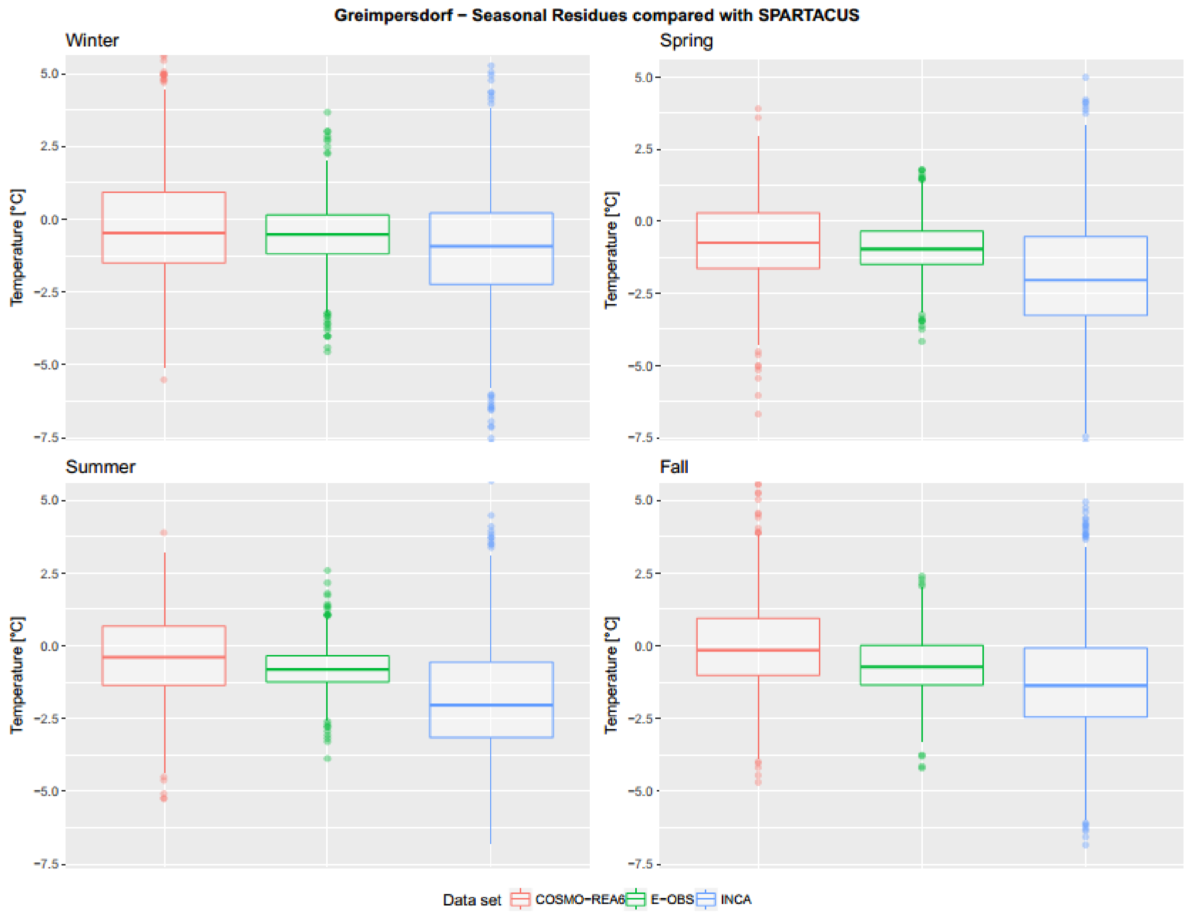

Figure 4-11: Seasonal residuals of temperature – Greimpersdorf

In general, the medians in winter display the best agreement with the SPARTACUS data, and the highest discrepancies – according to the median – are found during spring and summer. The IQR predicts a high variation of the residuals with values around 2.5°C in all subcatchments.

4.3.4 Maps of differences in the mean daily temperature

This chapter looks on Figure 10-43 to Figure 10-46, which present the mean daily temperature in Austria, predicted by each data set. For a comparison Figure 4-12 to Figure 4-14 display the differences of the mean daily temperature. The maps show the borders of the Austrian states and the research catchments of this thesis.

Looking on the maps it is easy to see that elevation has a significant impact on temperature in general. Moreover it is highly influencing the temperature forecast of SPARTACUS and INCA, which is perfectly seen due to the small resolution. With an increasing elevation, the temperature decreases. The Alps are identifiable in SPARTACUS and INCA just in looking on the distribution of the mean daily temperature. Moreover, the valleys are visible as well, with having a much higher temperature. In all data sets the highest mean daily temperature values occur in the southeastern parts of Austria, for example in Vienna, Burgenland, parts of Lower Austria and parts of Styria. Opposed, the coldest mean daily temperature among all data sets can be found in the highest regions summits of Austria, f.e. in Eastern Tyrol (Großvenediger, Großglockner) or Vorarlberg (Piz Buin).

Figure 10-45 represents the E-OBS data set and therefore the cell size is bigger. Comparing this map to SPARTACUS and INCA it is clear that due to this resolution the temperature forecast cannot be exact. As seen in Figure 4-13 this coarse resolution causes high residuals especially in the western, mountainous regions. In regions with a lower elevation, for example Vienna, Lower and Upper Austria, the results show better agreement for all data sets.

COSMO-REA6 is displayed in Figure 10-46, where the cell size is bigger than for SPARTACUS and INCA but smaller as in E-OBS. Therefore the results are better as in E-OBS and worse than SPARTACUS and INCA, as changes on a small-scale cannot be seen. Due to the resolution, errors can be found in the western areas, as shown in Figure 4-14. The eastern parts of Austria are predicted very well by COSMO-REA6 and the bias to SPARTACUS is small. Looking on the research area, the Salzach catchment shows high differences up to 6°C, whereas the Ybbs catchment mainly shows a bias smaller than 2°C.

For INCA the temperature values tend to be overestimating in areas with a higher elevation, and underestimating in areas with a lower elevation, as shown by Figure 4-12.

Generally the values of INCA and SPARTACUS agree very well, however higher differences agree again in areas with a complex terrain. When looking especially on Tyrol the yellow color indicates that INCA is overestimating mountains with a southern exposure, leading to the conclusion that one data set is taking exposure into account and the other one is not.

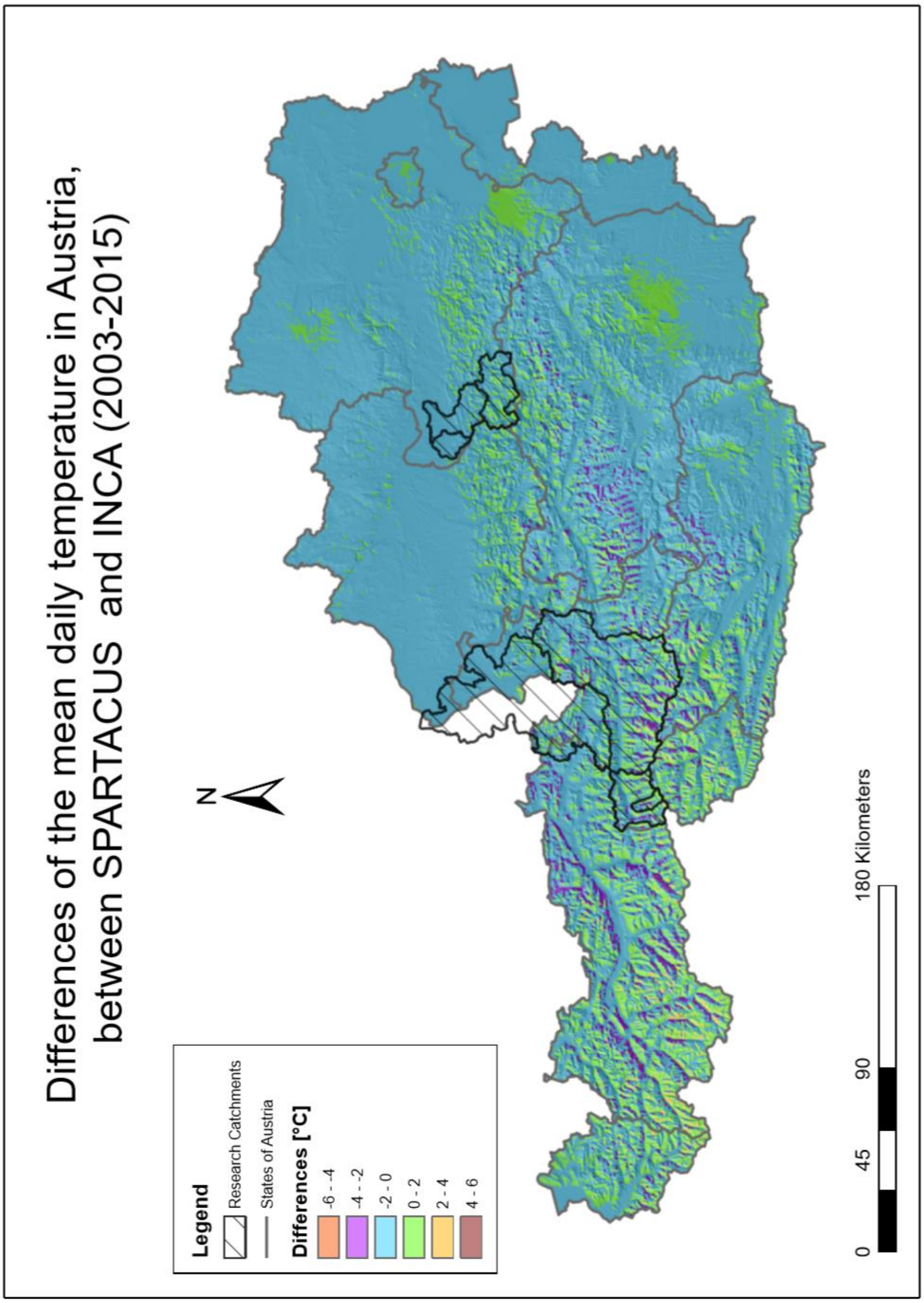

Figure 4-12: Difference of the mean daily temperature – SPARTACUS and INCA

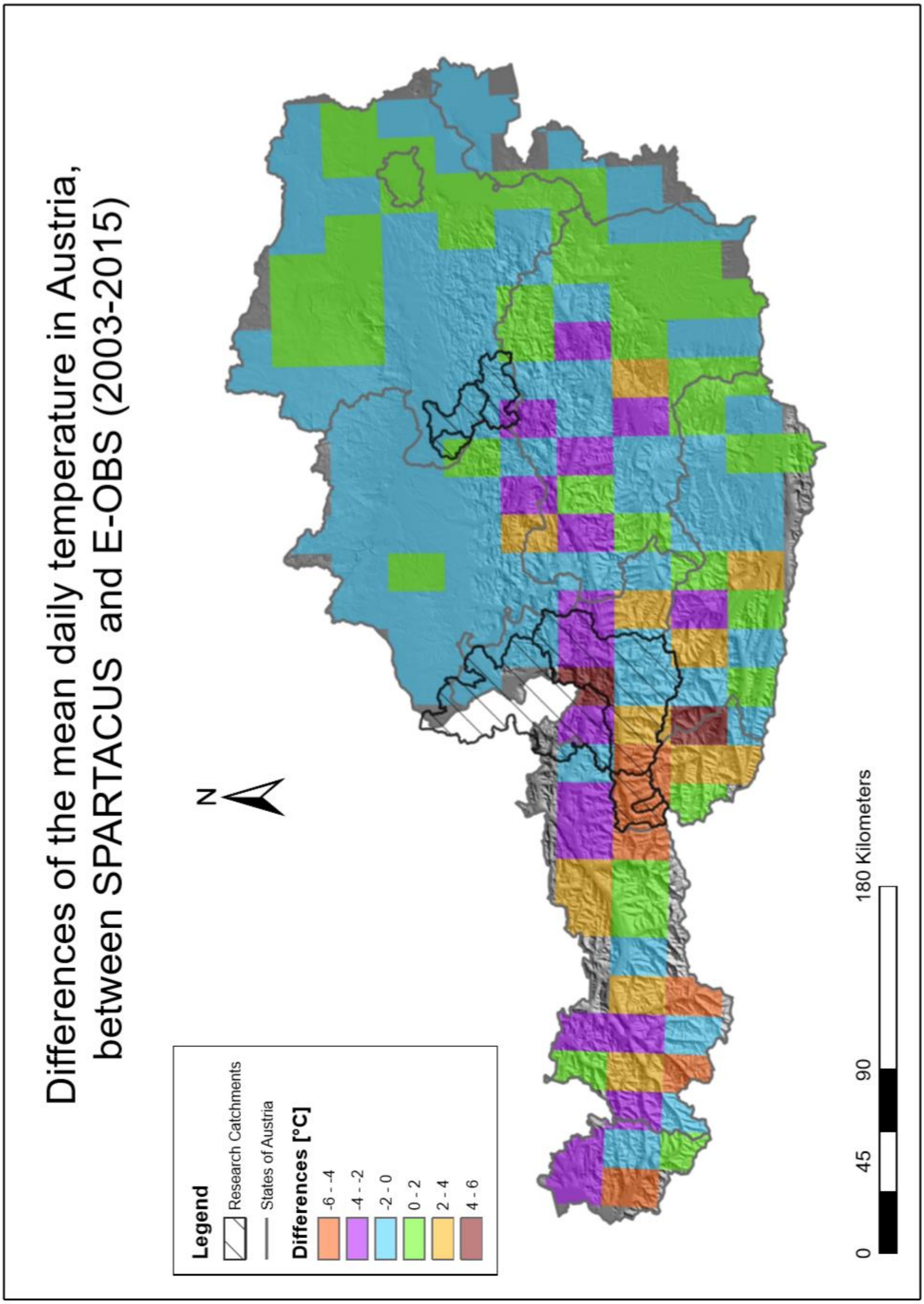

Figure 4-13: Differences of the mean daily temperature – SPARTACUS and E-OBS

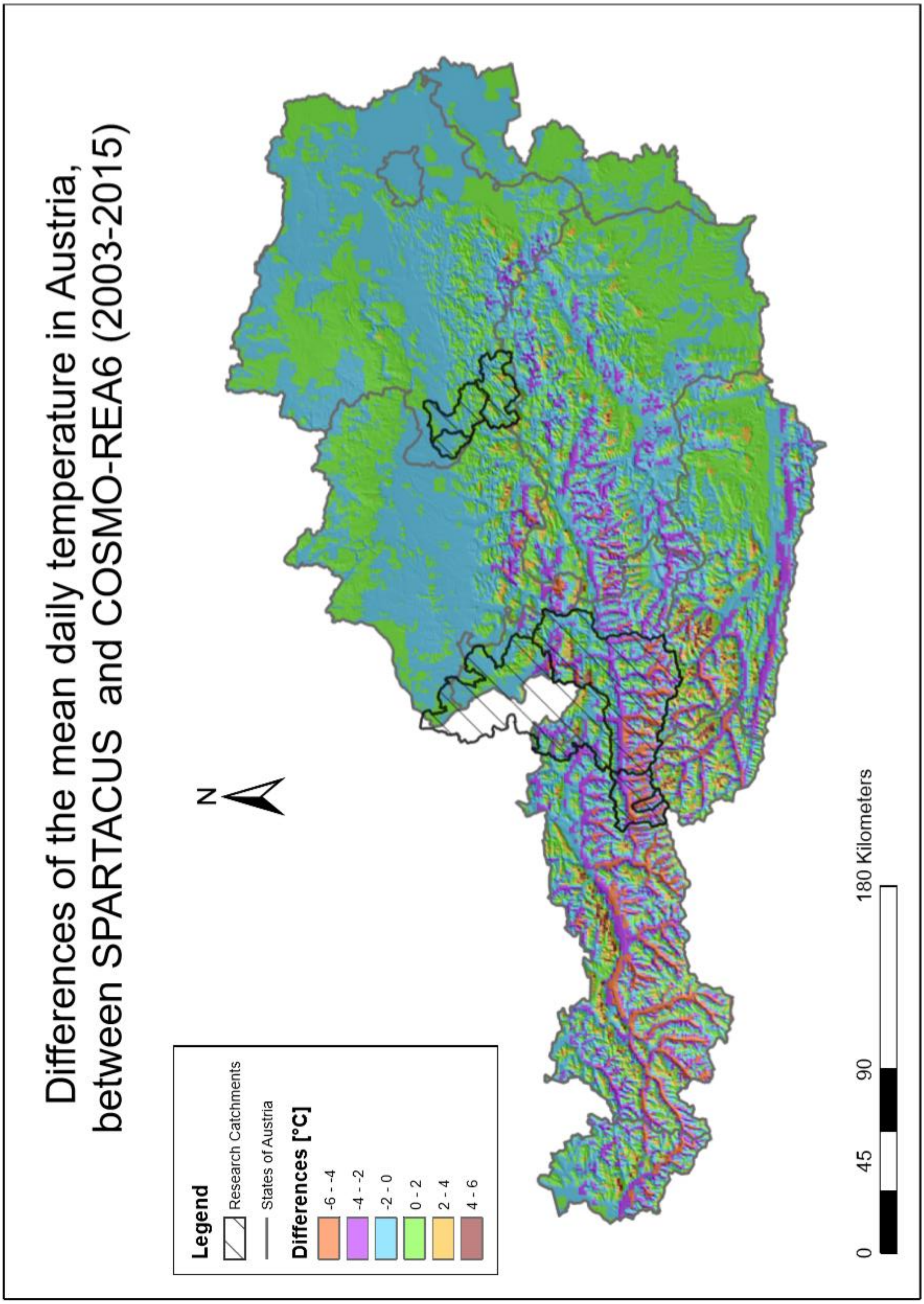

Figure 4-14: Differences of the mean daily temperature – SPARTACUS and COSMO-REA6

4.4 Data Plots – Precipitation

This chapter compares and assesses all plots on precipitation that are explained in chapter 3.4.2.

4.4.1 Mean monthly precipitation height

The mean monthly precipitation height is compared looking on the different catchments and the different data sets.

Salzach

The mean monthly precipitation height of the Salzach subcatchments can be found in Figure 10-13 to Figure 10-15. In all subcatchments the mean annual precipitation height from SPARTACUS is lowest among all data sets. There are large discrepancies in the variation of annual precipitation for all subcatchments. The best agreement concerning the interannual variability is found in Golling for all data sets (Figure 4-15). Also, the mean annual precipitation height has the best agreement in Golling among all subcatchments. The values in Golling are: 1443mm (SPARTACUS), 1569mm (INCA), 1682mm (E-OBS) and 1689mm (COSMO-REA6).

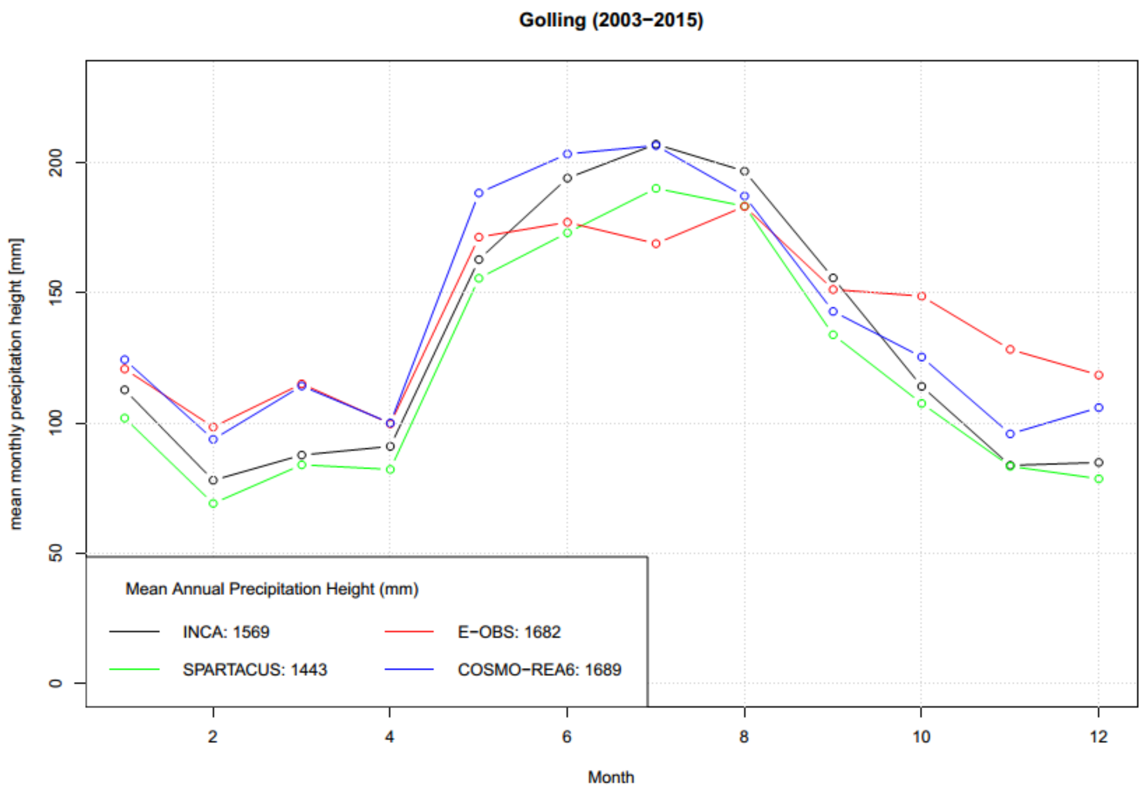

Figure 4-15: Mean monthly precipitation height – Golling

In all subcatchments INCA is overestimating the mean monthly precipitation height in summer, especially in Sulzau (Figure 4-16), where the values are higher for half of the year. For spring, fall and winter the bias between SPARTACUS and INCA gets smaller and the interannual variability is displayed reasonably enough. For Sulzau and Mittersill E-OBS underestimates in summer, late spring and early fall and overestimates in winter, late fall and early spring. In Golling the values are only smaller in July compared to SPARTACUS. The mean monthly precipitation height of August is estimated lower in COSMO-REA6 than it is in SPARTACUS. For the rest of the year COSMO-REA6 overestimates the precipitation height.

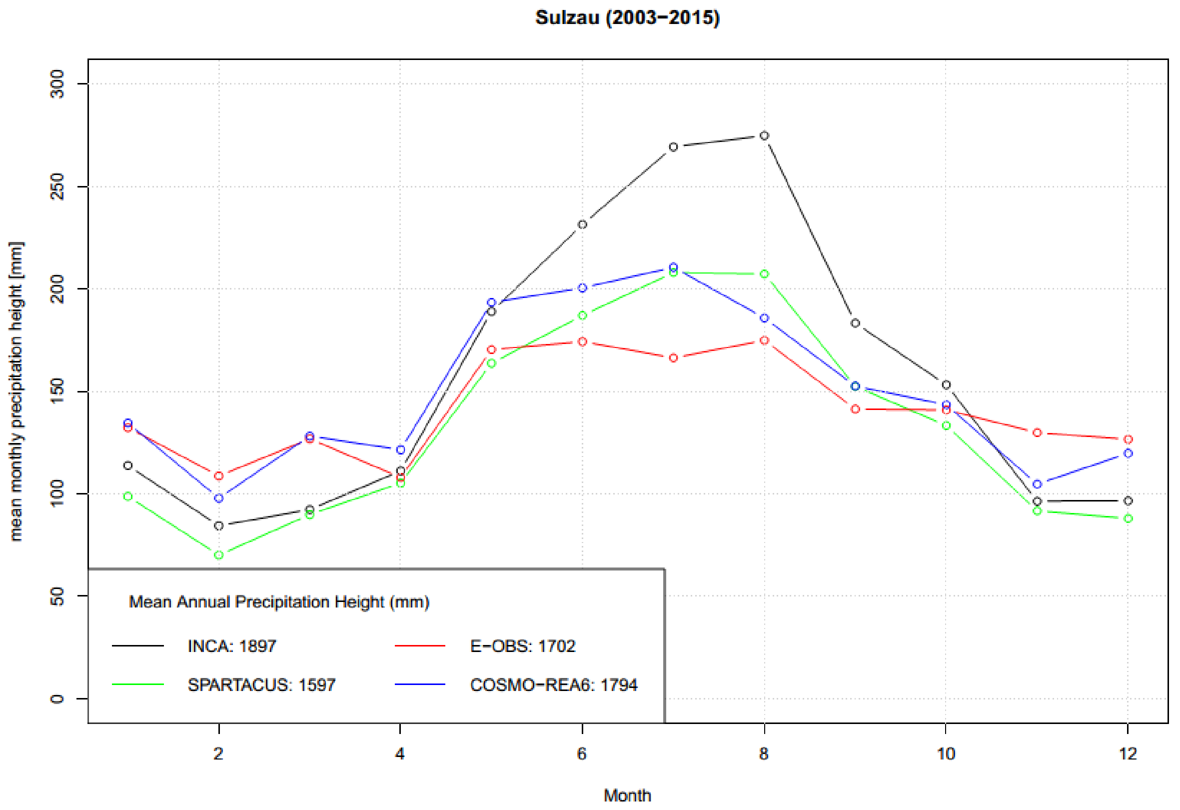

Figure 4-16: Mean monthly precipitation height – Sulzau

Ybbs

Figure 10-16 to Figure 10-18 show the mean monthly precipitation height for the Ybbs subcatchments. Whereas in the Ybbs catchment the mean long-time precipitation height in INCA is higher than it is in SPARTACUS, it is lower in E-OBS for all subcatchments. COSMO-REA6 estimates a lower mean annual precipitation height for Opponitz (Figure

4-17) and Krenstetten and a higher value for Greimpersdorf. INCA predicts higher precipitation heights for all months and all subcatchments, apart from January, February and March in Opponitz. The highest differences between INCA and SPARTACUS span almost 50 mm in the summer. INCA seems to match SPARTACUS best in spring and winter.

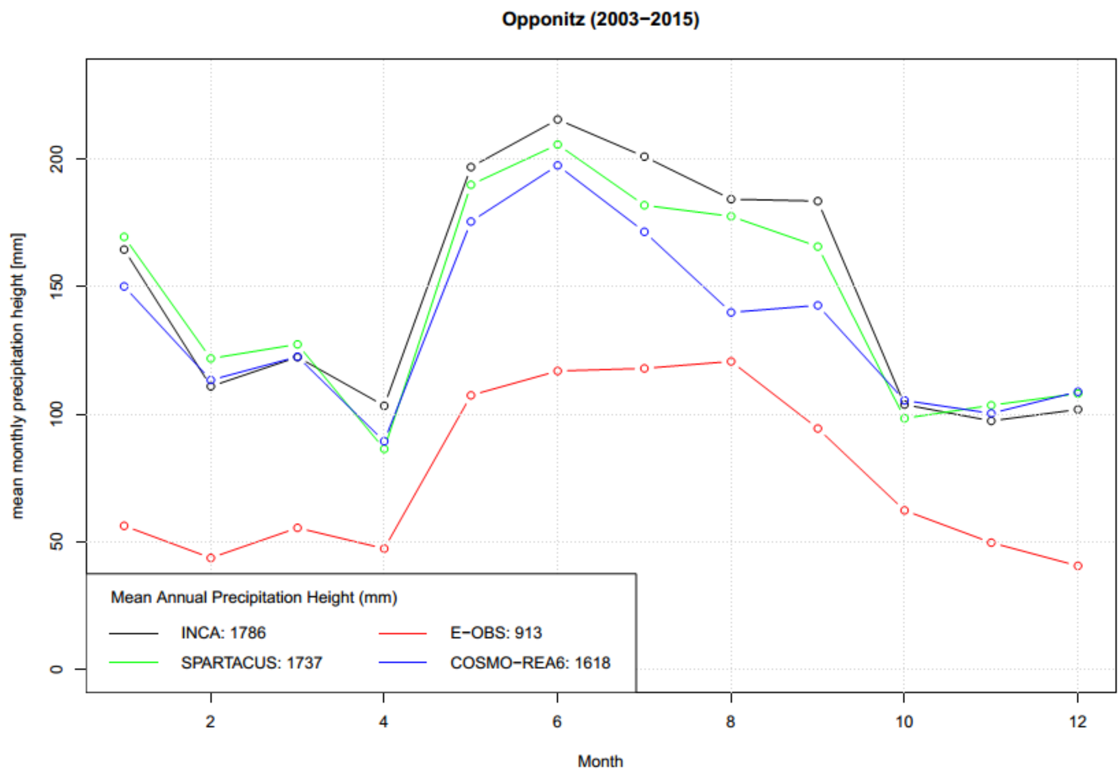

Figure 4-17: Mean monthly precipitation height – Opponitz

E-OBS has much smaller values than SPARTACUS and it does not match the interannual variation very well. COSMO-REA6 underestimates SPARTACUS in Krenstetten and in Opponitz, and overestimates in Greimpersdorf. The interannual agreement among all data sets is best for spring, fall and winter. In summer the differences are in general higher. When looking only on INCA, SPARTACUS and COSMO-REA6 it appears that the differences are smaller in Opponitz as compared to the other Ybbs subcatchments. This is also shown by the long-term precipitation height in Opponitz (Figure 4-17); 1737mm (SPARTACUS), 1786mm (INCA) and 1618mm (COSMO-REA6).

4.4.2 Mean annual precipitation height

The mean annual precipitation height predicted by the data sets is compared, looking separately on Salzach and Ybbs.

Salzach

The mean annual precipitation height of the Salzach subcatchments is shown by Figure 10-19 to Figure 10-21. SPARTACUS is constantly underestimated by all other data sets in all subcatchments. INCA appears to predict peaks too extreme, resulting in differences up to 400 mm. Especially in 2013 INCA shows the largest differences among all data sets, as for example seen in Figure 4-18.

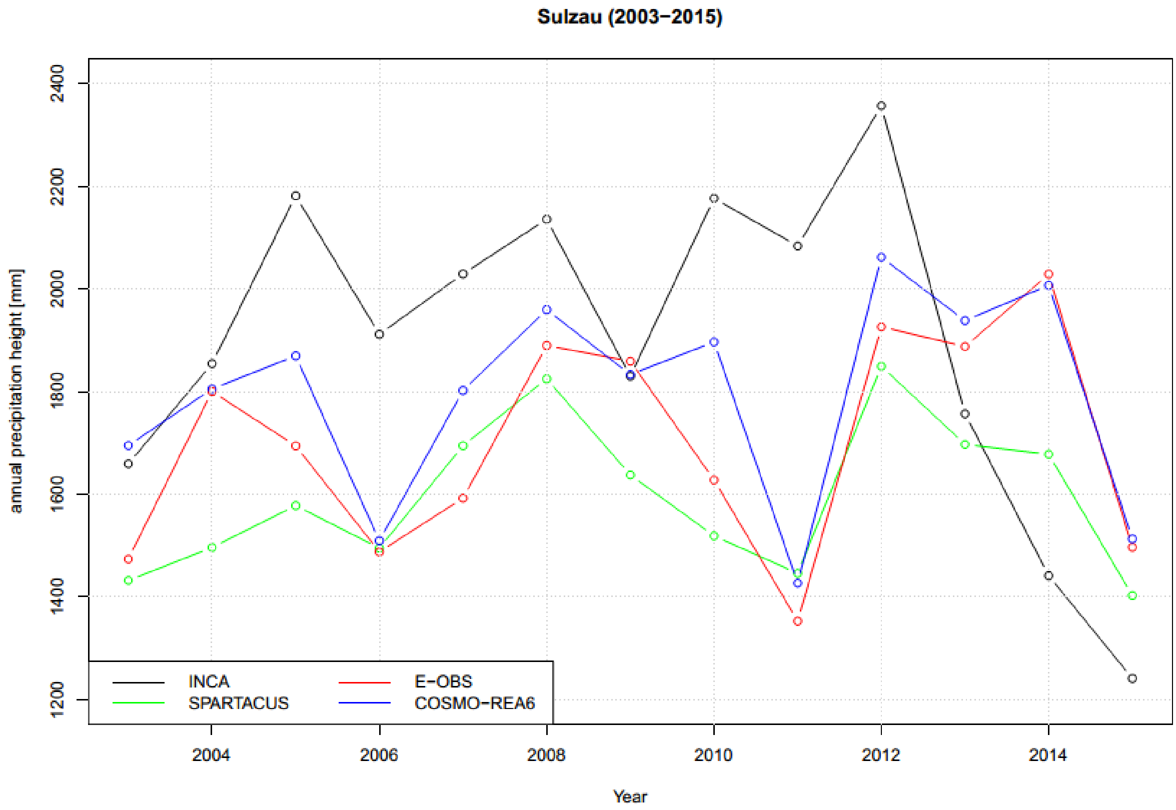

Figure 4-18: Annual precipitation height – Sulzau

E-OBS and COSMO-REA6 have similar relative changes in annual precipitation heights for all subcatchments. However, this trend does not agree with SPARTACUS. The data sets scatter highly, and a constant bias is difficult to see. Most of the years the magnitudes differ around 100-200mm for all data sets and subcatchments.

Ybbs

Figure 10-22 to Figure 10-24 display the mean annual precipitation height in the Ybbs subcatchment. The data sets predict mostly right trends, regarding precipitation sum going up or down. In the Ybbs catchment the trend agrees more, than it does in the Salzach catchment. However, the differences in magnitude are very high. E-OBS is constantly underestimating SPARTACUS. Although they are shifted sometimes more than 1000mm the relative changes from year to year seem to be reasonable similar between E-OBS and SPARTACUS. INCA is constantly overestimating SPARTACUS, apart from Opponitz in 2003-2006, as seen in Figure 4-19.

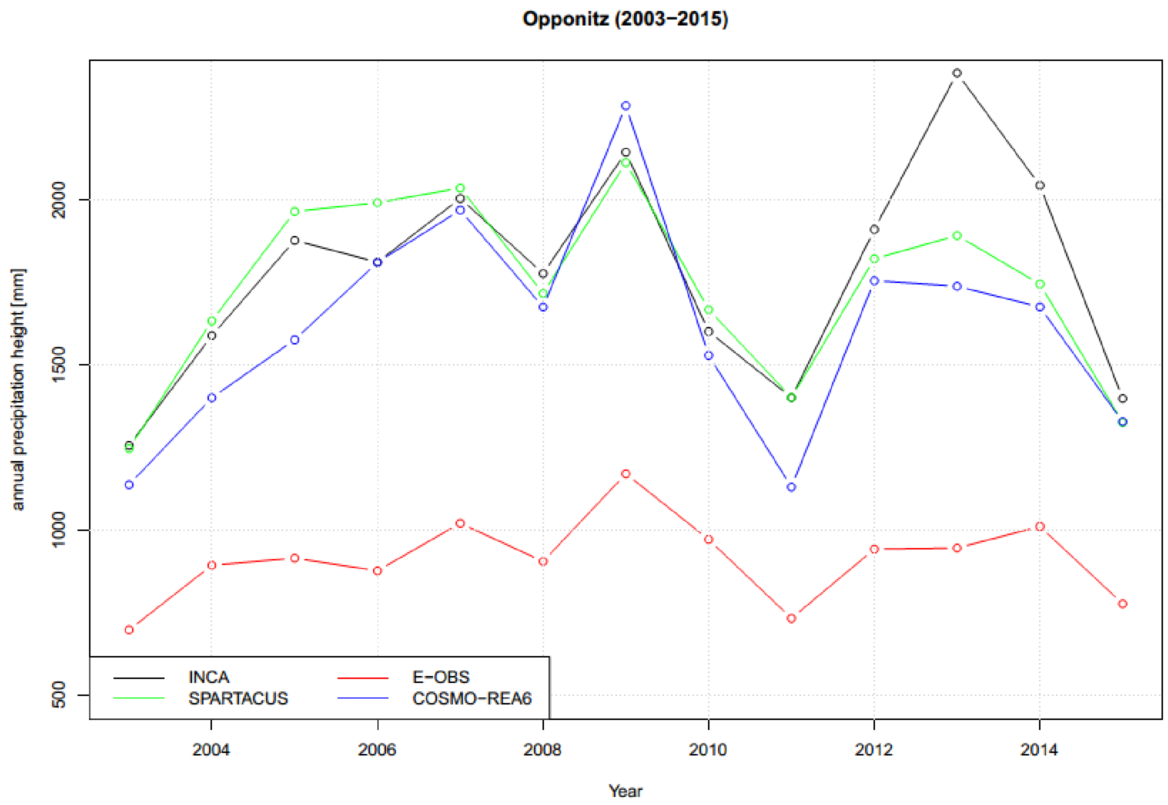

Figure 4-19: Annual precipitation height – Opponitz

Especially in the last few years the discrepancies between SPARTACUS and INCA are high, up to a difference of 700mm. The peak in 2013 predicted by INCA is highly overestimating. In Krenstetten and Opponitz COSMO-REA6 is underestimating SPARTACUS, with largest differences in extreme wet or extreme dry years. For Greimpersdorf COSMO-REA6 is overestimating and again producing peaks that are too high. In 2009 the difference is nearly 500mm.

4.4.3 Sum of precipitation over time

The precipitation sum predicted by the data sets is compared, looking separately on the Salzach and Ybbs catchment. All results are summed up in Table 4-14 and Table 4-15. The first number in each cell is the absolute result and the second number is the relative bias, compared to SPARTACUS.

Salzach

Figure 10-25 to Figure 10-27 display the precipitation sum over all years and subcatchments from all four data sets in the Salzach catchment. In Salzach the precipitation sum of SPARTACUS is constantly lower than from all other data sets. The largest discrepancies among all data sets can be found in Sulzau where the sum of precipitation over 13 years is overestimated by 19% from INCA compared to SPARTACUS as seen in Figure 4-20.

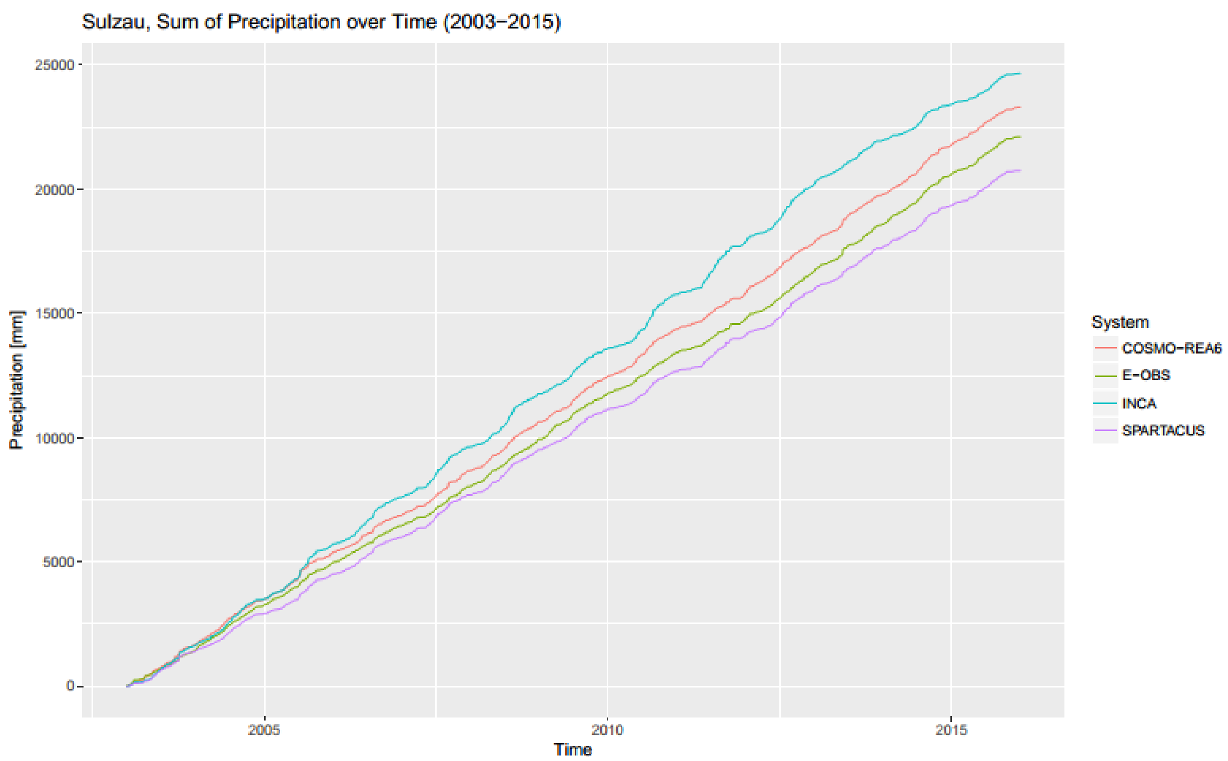

Figure 4-20: Sum of precipitation – Sulzau

While for E-OBS and COSMO-REA6 the highest match of the all year precipitation sum among the data sets can be found in Sulzau, for INCA it is shown in Golling, as displayed in Table 4-14.

Table 4-14: Precipitation sum 2003-2015, Salzach

Subcatchment	SPARTACUS [mm]	INCA [mm]	COSMO-REA6 [mm]	E-OBS [mm]
Sulzau	20757	24662 (118.8%)	23323 (112.3%)	22123 (106.5%)
Mittersill	19279	21337 (110.7%)	22100 (114.6%)	21660 (112.4%)
Golling	18848	20400 (108.2%)	21952 (116.5%)	21868 (116.0%)

Ybbs

Figure 10-28 to Figure 10-30 display the precipitation sum over all years and subcatchments from all four data sets in the Ybbs catchment. In general, the agreement of all data sets is higher in the Salzach catchment than in the Ybbs catchment. For all catchments over all years INCA produces the highest precipitation sum, SPARTACUS the second highest, COSMO-REA6 the second lowest and E-OBS the lowest precipitation sum, as for example seen in Figure 4-21.

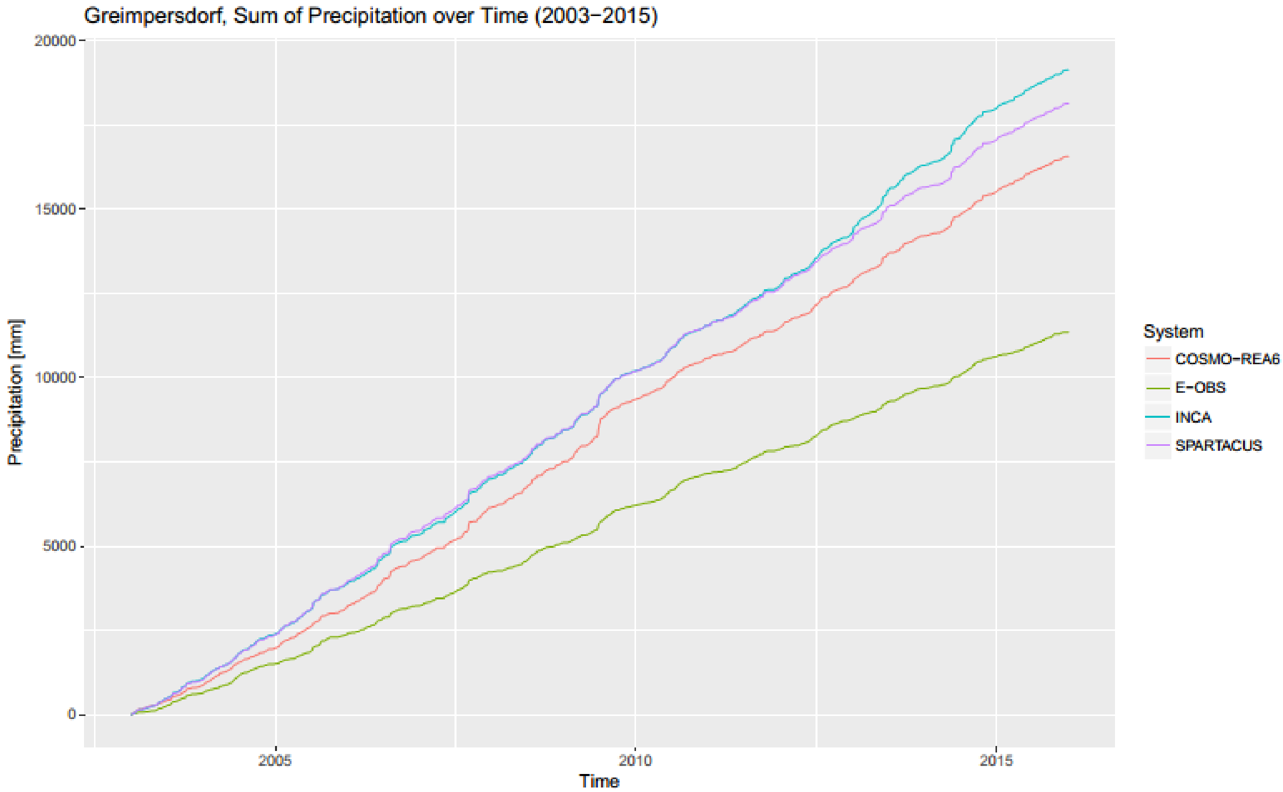

Figure 4-21: Sum of precipitation – Greimpersdorf

Furthermore, in all catchments the estimations of COSMO-REA6 are closer to the estimations of SPARTACUS compared to E-OBS. INCA produces the best agreement with SPARTACUS, predicting a precipitation sum only 2% higher than SPARTACUS in Opponitz, as shown in Table 4-15. The precipitation sum of E-OBS predictions is highly underestimating compared to the other data sets. The highest discrepancy is displayed in Opponitz where the relative bias from E-OBS to SPARTACUS is nearly 50%.

Table 4-15: Precipitation sum 2003-2015, Ybbs

Subcatchment	SPARTACUS [mm]	INCA [mm]	COSMO-REA6 [mm]	E-OBS [mm]
Opponitz	22576	23219 (102.8%)	21030 (93.15%)	11867 (52.6%)
Greimpersdorf	18123	19122 (105.5%)	16557 (91.4%)	11350 (62.6%)
Krenstetten	13296	15401 (115.8%)	11527 (86.7%)	10517 (79.1%)

4.4.4 Boxplots of seasonal residuals in precipitation

This chapter compares the boxplots of the seasonal residuals in precipitation on a daily basis that can be found in the appendix. For both, Salzach and Ybbs, an overview of the data is given and then each data set is assessed, using the information provided by the boxplots.

4.4.4.1 Salzach

Figure 10-37 to Figure 10-39 display the seasonal residuals in precipitation for the Salzach catchment. The median is located around 0°C for all catchments and seasons. The range of the INCA data are much higher than the range of COSMO-REA6 and E-OBS. During summer the IQR of all data sets is higher than during the other three seasons.

COSMO-REA6

The variation of the middle 50% is slightly higher in spring and summer than it is in winter and fall. Throughout winter, spring and fall the residuals between the median and the 3rd quartile, which is also where the residuals show an overestimation, are more spread than the area between the median and the 1st quartile. During summer the variation for the residuals which are over- or underestimating SPARTACUS is very similar, with a higher scatter for the overestimation values in Golling and Mittersill (Figure 4-22).

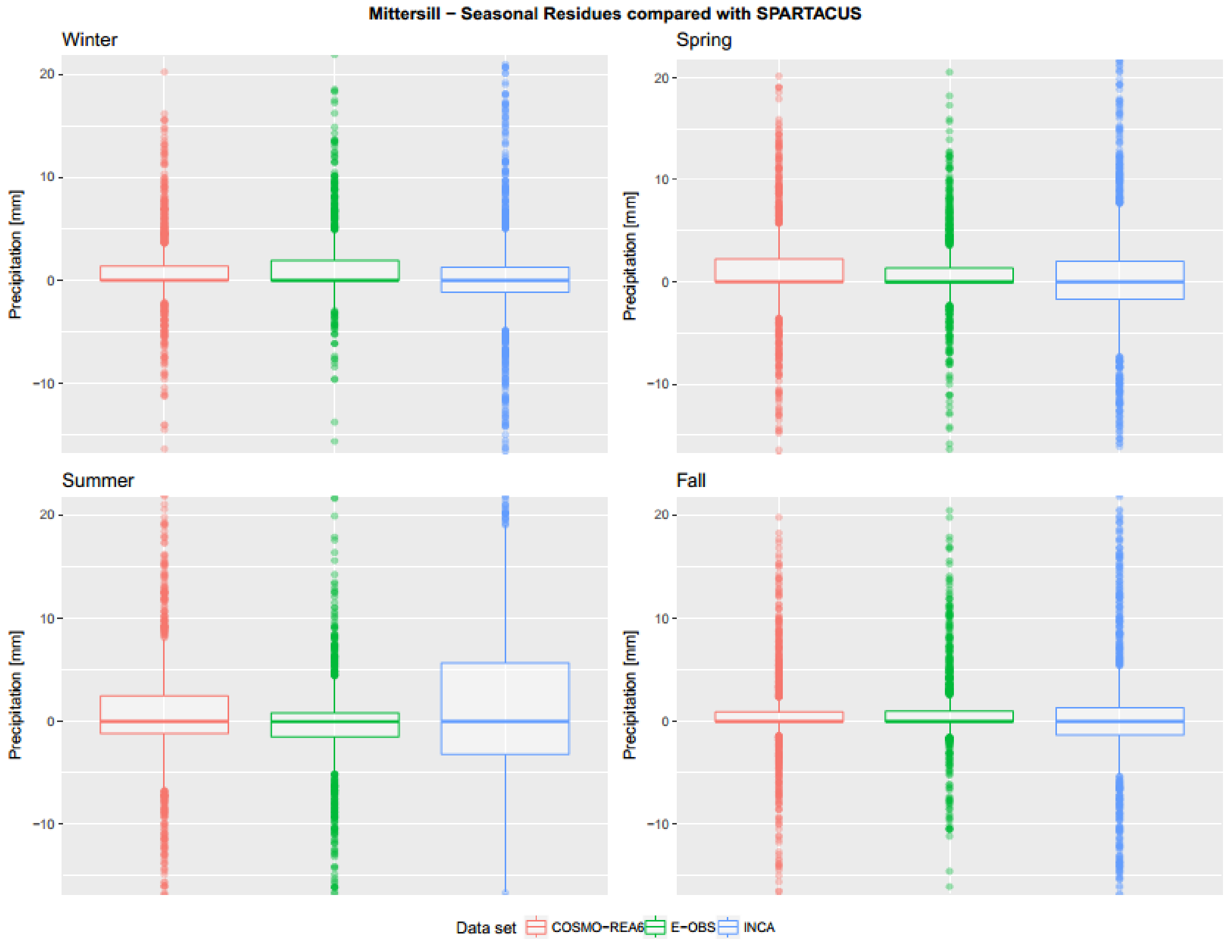

Figure 4-22: Seasonal residuals of precipitation – Mittersill

E-OBS

Compared to the other data sets, E-OBS show the smallest IQR. Especially during fall the variation of the residuals is small. With values of 2.5mm/day the IQR is highest in Sulzau. The range of the middle 50% is higher in winter and summer than it is during spring and fall. While in winter, spring and fall the residuals that show an overestimation are scattered highly, for summer the values of underestimation are more distributed.

INCA

According to the IQR values the smallest variation of the residuals can be found during winter and fall. The highest IQR can be found in summer throughout all catchments. The residuals are distributed around 0mm very similar, although a tendency can be seen, that the residuals which are overestimating SPARTACUS are larger scattered than the residuals which display an underestimation.

4.4.4.2 Ybbs

Figure 10-40 to Figure 10-42 show the seasonal residuals in precipitation for the Ybbs subcatchments. The residuals in INCA are highly distributed, especially in summer the range of the residuals is much larger than from COSMO-REA6 and E-OBS. COSMO-REA6 shows a tendency of overestimating the data, while E-OBS tend to underestimate the data. In all subcatchments the medians of the data sets are very close to 0.

COSMO-REA6

The IQR is higher in winter and summer than in spring and fall for all subcatchments. While the middle 50% show that the residuals during spring and fall are around 1mm/day in summer and winter they are up to 2.5mm/day. In all subcatchments the median is 0mm/day. In winter the residuals that show an overestimation, therefore the residuals between the median and the 3rd quartile, are higher distributed than the residuals which predict an underestimation. However, during summer it is the other way around. Meaning, that the residuals between the median and the 1st quartile that show an underestimation, are larger variated than the residuals which display an overestimation.

E-OBS

The IQR of E-OBS alters similarly as the IQR of COSMO-REA6. While the middle 50% span a smaller range during spring and fall, the IQR is higher during winter and summer in all subcatchments. The minimum values of the IQR are 0.5mm during fall (Greimpersdorf) 3mm during winter (Opponitz). In Opponitz the IQR values for all seasons are twice the size of the IQR from the other subcatchments (Figure 4-23). The IQR, whiskers and outliers show that the lower 50% of the residuals are more scattered than the upper 50% of the residuals.

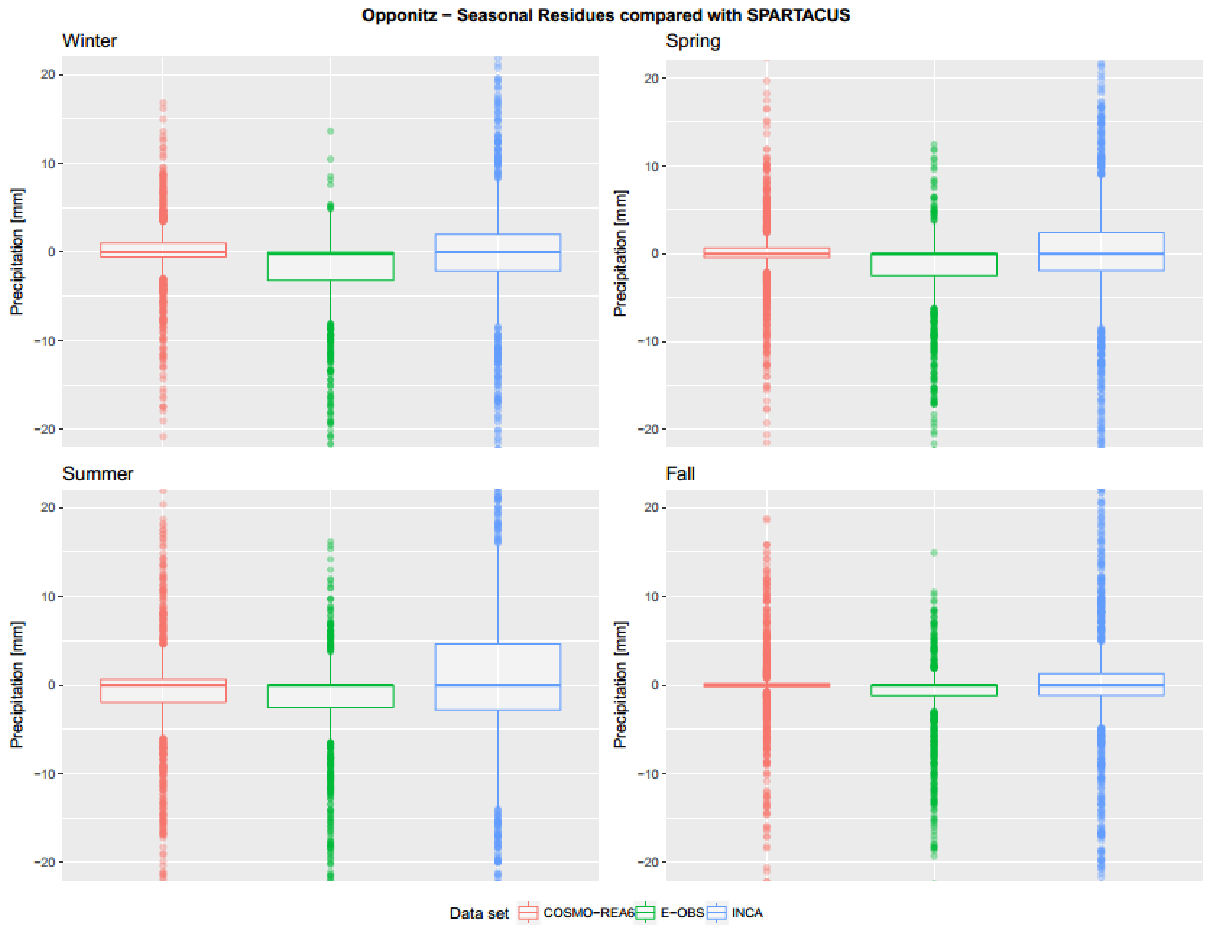

Figure 4-23: Seasonal residuals of precipitation – Opponitz

INCA

The variation of INCA is much higher than the other data set. With values up to 7.5mm the IQR is highest during summer season for all subcatchments. The range of the IQR is smallest during fall with the value being 1.25mm, and it changes similarly in spring and winter. Throughout all seasons the IQR is highest in Opponitz. For INCA the residuals are most scattered for the upper 50%, so the data between the median and the highest value.

4.4.5 Maps of differences in the mean annual precipitation sum

This chapter looks on Figure 10-47 to Figure 10-50, which present the mean annual precipitation sum in Austria, predicted by each data set. For a comparison Figure 4-24 to Figure 4-26 display the differences of the mean annual precipitation sum. The maps show the borders of the Austrian states and the research catchments of this thesis. Looking on the maps it is easy to see that elevation has a huge impact on precipitation in general. Moreover it is highly influencing the precipitation forecast of SPARTACUS and INCA. The precipitation sum rises with an increasing elevation. The Alps are identifiable in SPARTACUS and INCA just in looking on the distribution of the precipitation sum. The valleys are visible as well, with having a much lower precipitation sum. According to Figure 10-47, Figure 10-48 and Figure 10-50 the highest mean annual precipitation sums occur north of the Alps, which can be explained by the blocking effect of the Alps. Opposed, the lowest mean annual precipitation sum can be found in the eastern parts of Lower Austria and Vienna (Kienberger, Lang, and Zeil 2009).

Figure 10-49 represents the E-OBS data set and therefore the cell size is bigger. Comparing this map to SPARTACUS and INCA it is clear that due to this resolution the precipitation forecast cannot be exact and moreover this map shows wrong results. As seen in Figure 4-13 this coarse resolution causes high residuals especially in the western, mountainous regions. In general the majority of the precipitation data in Austria predicted by E-OBS is underestimating, compared to SPARTACUS. This is also confirmed by other plots compared in this chapter. In the Ybbs catchment for example an underestimation is shown, similar to the data plots in this chapter. In Salzach the results stated before are quite good for E-OBS, which is explained when looking on Figure 10-49: As the different precipitation sums are averaged, in the end a good result is shown.

COSMO-REA6 is displayed in Figure 10-50, where the resolution is bigger than for SPARTACUS and INCA but smaller as in E-OBS. Therefore the results are better as in E-OBS and worse than SPARTACUS and INCA, as changes on a small-scale cannot be rightly predicted. Figure 4-26 shows that whereas in the western parts the majority of the cells show an overestimation of COSMO-REA6 compared to SPARTACUS, in the eastern parts the data are mainly underestimated. These findings agree with other results outlined in this chapter.

For all data sets the results show better agreement in the states, with a lower elevation, for example Vienna and Lower Austria. For INCA the precipitation sum shows best results in Vienna, Burgenland and Northern Lower and Upper Austria. Generally the values of INCA and SPARTACUS agree well, however higher differences occur in areas with a complex terrain. The findings in this chapter, that the INCA data set predicts generally more precipitation than SPARTACUS, is supported by Figure 4-12.

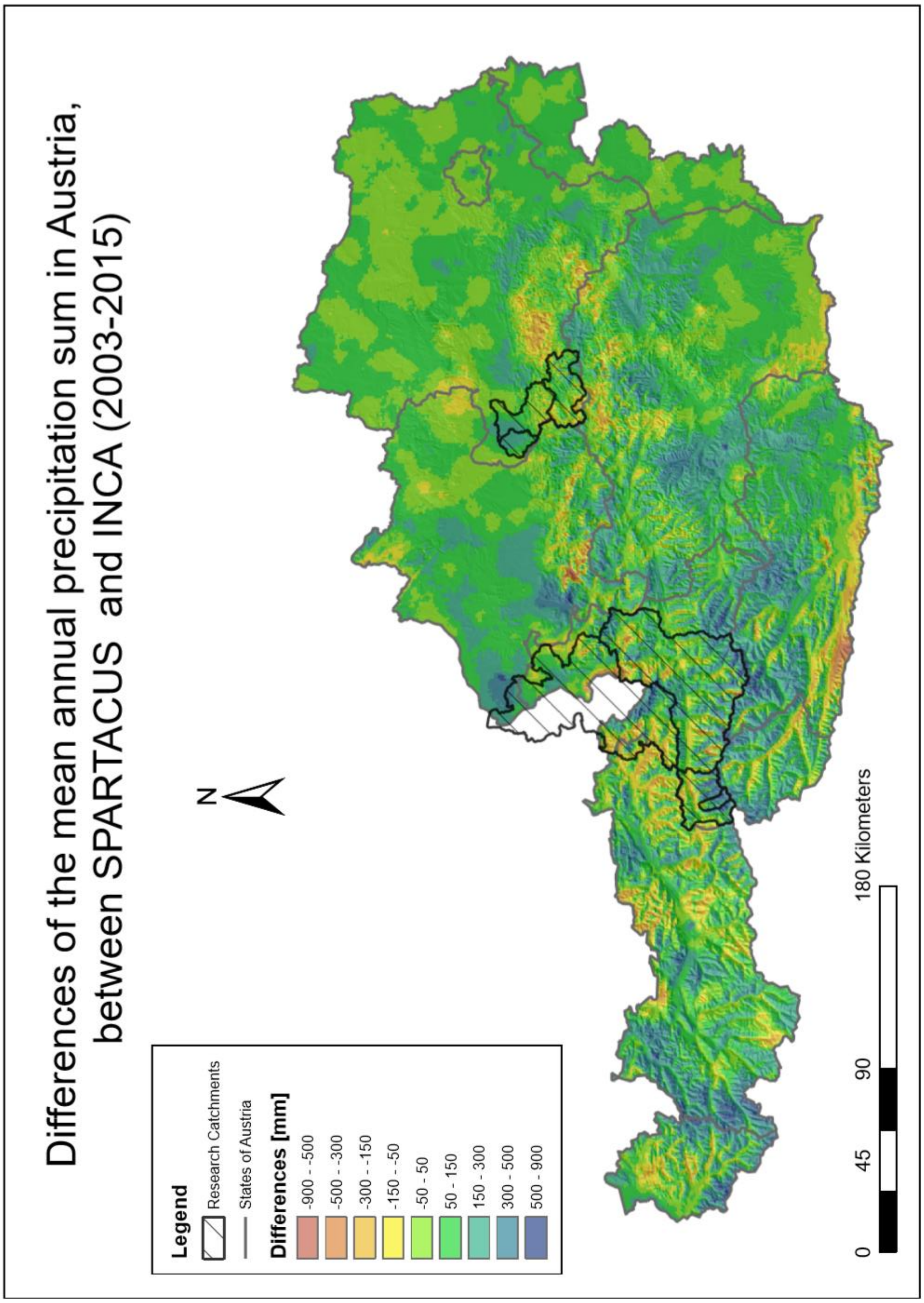

Figure 4-24: Differences of the mean annual precipitation sum – SPARTACUS and INCA

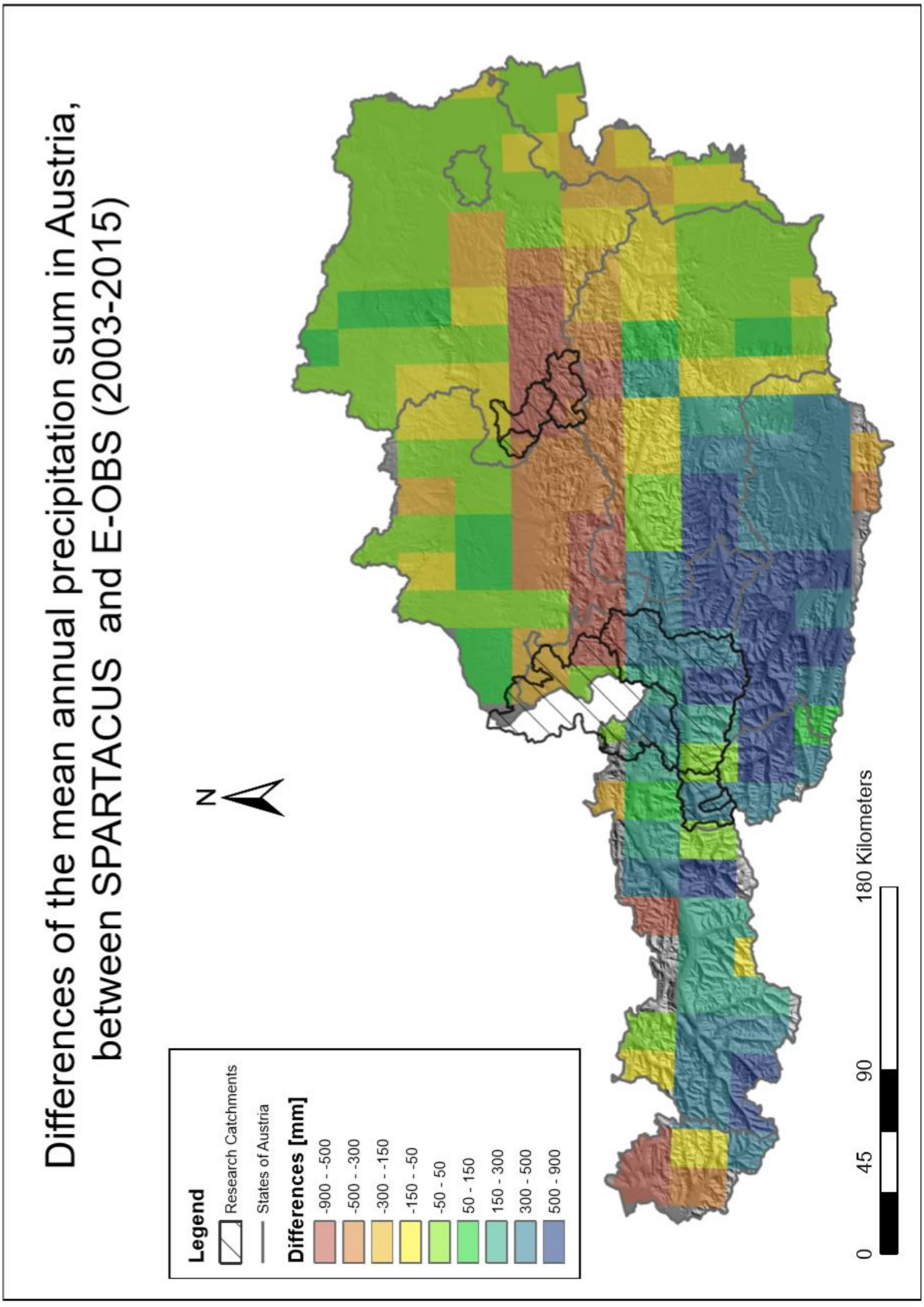

Figure 4-25: Differences of the mean annual precipitation sum – SPARTACUS and E-OBS

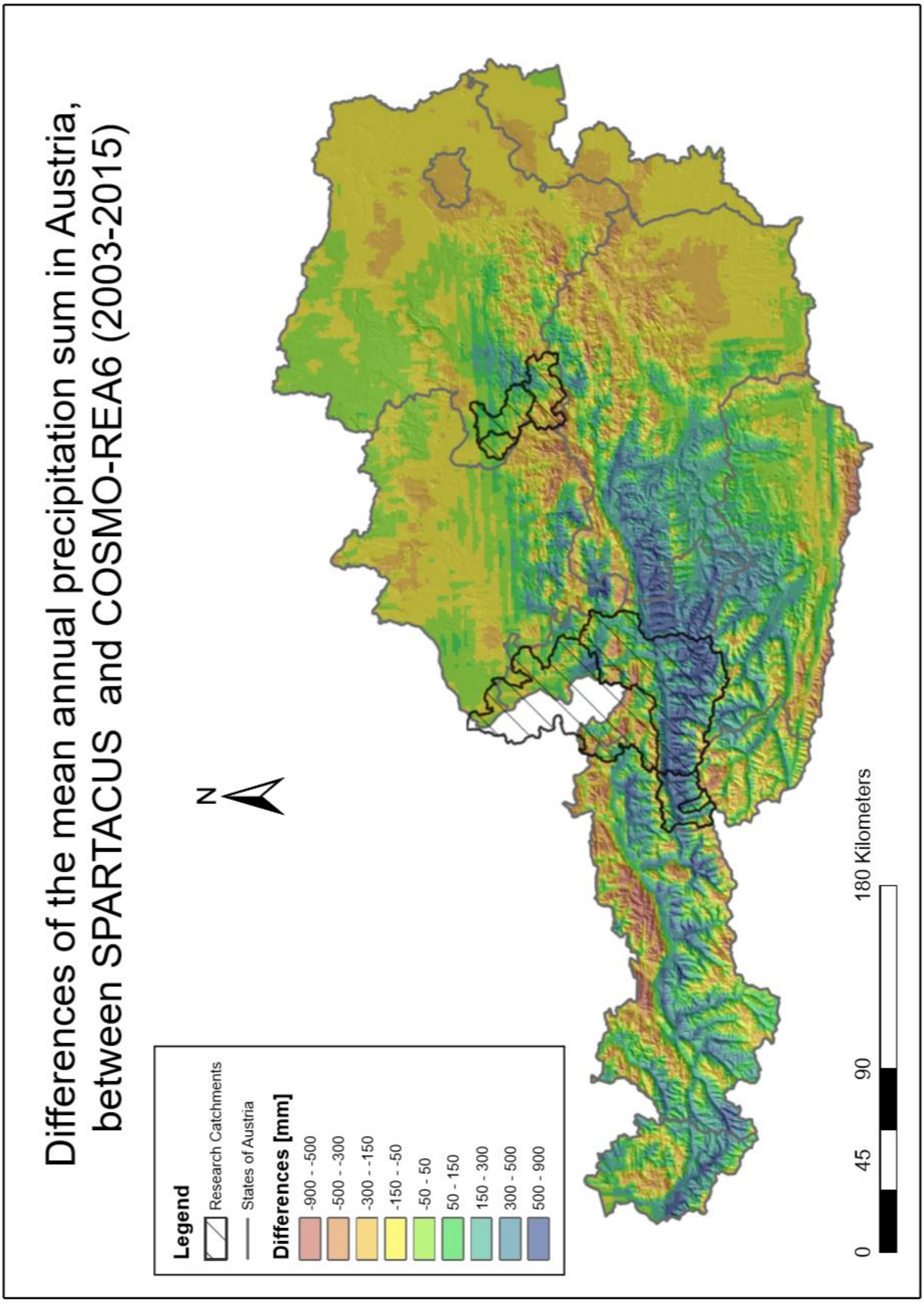

Figure 4-26: Differences of the mean annual precipitation sum – SPARTACUS and COSMO-REA6

5. Interpretation and Conclusion

In this chapter the comparison and assessment of chapter 4 is summarized and put into context. It is separately looked on precipitation and temperature. Moreover, limitations to this thesis are outlined. A statement with a recommendation and future prospects are provided in the end.

Looking on all different comparisons, it is obvious that regularities of the data are difficult to find as the data sets highly scatter. However, some conclusions – which are valid for all catchments – can be drawn and are listed in the following.

5.1 Temperature

The following regularities are found valid for all comparisons.

- A reasonable consistent interannual variability of mean monthly temperature is displayed.

A very high correlation can be found between the daily data sets and SPARTACUS. This means that the temperature values follow a very similar variation throughout the year. While for INCA the correlation is higher in winter, COSMO-REA6 and E-OBS show a higher R^2 during summer period. Moreover, the changes of mean annual temperature, although shifted, have a high agreement. The shift of the mean annual temperature is highest in Greimpersdorf (1.5°C). While for E-OBS, INCA and COSMO-REA6 continuous data for the whole catchments were available, the results in SPARTACUS average the data, without having the information over Germany. This can be an explanation to this result.

- Days with a mean temperature below 0°C tend to be estimated better in smaller catchments with a higher elevation.

Extreme events are crucial to hydrological models: warm days increase evapotranspiration and temperature values lower than 0°C determine that precipitation is falling as snow. Snow contributes to accumulating precipitation in the catchment, rather than draining into the river. The data sets show similarities in over- or underestimating the numbers of days for extreme events. The best results are found for the smaller catchments with a higher elevation. While frost days tend to be overestimated, warm days tend to be underestimated by all data sets. As INCA, E-OBS and COSMO-REA6 show an agreement of over- and underestimating, this might be an indication that SPARTACUS is not rightly predicting the frequency of meteorological events.

- INCA has the highest daily bias and tends to underestimate temperature

Looking on all data, INCA shows the highest bias, with maximum differences in Greimpersdorf. The daily residuals to SPARTACUS have a much larger variation than all other data sets. Therefore, the daily values are spread, which is also displayed by high IQR-values up to 2.5°C. The correlation of INCA is higher in winter than it is in summer.

- The comparisons show that COSMO-REA6 and E-OBS have a higher correlation to SPARTACUS during summer.

As all plots and calculations indicate a better agreement during summer, the reliability of the hydrology model during summer can be expected to increase as well. Surprisingly, E-OBS shows a very good correlation in both catchments, although shifted when looking on the mean monthly or annual temperature. Moreover, the bias of the residuals indicates a smaller variation than all other data sets. Meaning that a systematic bias may be possible to find and correct before using the data in hydrological modelling.

- All data sets agree better in regions with a lower elevation. Opposed, in regions with a complex topography the results show a higher bias.

The weather stations Rudolfshütte (Salzburg, 2317m) is the 7th highest weather station in Austria. Therefore in areas with high elevation observation data is hardly available, which is a reason for getting worse results.

5.2 Precipitation

The following regularities are found for precipitation.

- The E-OBS data set cannot be used for modelling in Austria / the Alpine region

Kobold und Sušelj published a paper on the impact of precipitation data on hydrologic models in Slovenia. Although this paper covers Slovenia, it still gives an idea of the impact of precipitation on runoff models. Furthermore, both Austria and Slovenia are characterised by a complex topography. Countries with complex topography call for input data, which is able to reproduce small-scale phenomena on a fine resolution (Kobold and Sušelj 2005).

Looking at all different statistic tests and maps, it is obvious that E-OBS is very strongly dependent on the observation stations. As in Austria there are only six stations which are used for the interpolation in E-OBS, the patterns of precipitation and small-scale phenomena can not be shown correctly. Overall a better agreement is shown in Salzach as there is one station in Salzburg and another one at Sonnblick, contributing to a reasonable interpretation. However, when looking on Ybbs – where the next observation station is in Vienna – the data have a very high bias, with a high underestimation of precipitation up to a relative bias of 60%.

- The resolution of INCA and SPARTACUS is more suitable for a hydrological model.

As outlined in chapter 1.1 the resolution of the input data can be the determining factor in choosing a data set. Gampe and Ludwig (2017) state, like other papers, that in general a higher spatial resolution results in a better representation of the local patterns. When looking only on Austria INCA and SPARTACUS provide the best resolution with a 1x1 km raster, meaning that their predicted values can vary accordingly to the complex topography, as seen in chapter 4.4.5. On the other hand, COSMO-REA6 and E-OBS cover a larger region. So if the focus is put just on Austria, INCA and SPARTACUS are the best choice, however when looking on a larger research area COSMO-REA6 can be the better option (Gampe and Ludwig 2017).

- All data sets agree better in regions with a lower elevation. Opposed, in regions with a complex topography the results show a higher bias.

The weather stations Rudolfshütte (Salzburg, 2317m) is the 7th highest weather station in Austria. Therefore in areas with high elevation observation data is hardly available, which is a reason for getting worse results. The differences in the western parts of Austria are higher than the differences in the eastern parts of Austria.

- COSMO-REA6 is overestimating precipitation in regions with a higher elevation.

COSMO-REA6 shows that whereas in the western parts of Austria the majority of the data cells show an overestimation compared to SPARTACUS, in the eastern parts the data are mainly underestimating. Additionally, while an overestimation of the Salzach catchment is shown by COSMO-REA6 an underestimation of the Ybbs catchment is found. This leads to the conclusion that COSMO-REA6 is generally overestimating precipitation in regions with a higher elevation.

- INCA overestimates precipitation compared to SPARTACUS

Comparing daily values of SPARTACUS and INCA, no correlation is recognizable. INCA overestimates SPARTACUS, with highest discrepancies in summer. The peeks in INCA seem to be displayed far too high, resulting in differences of the mean annual precipitation height up to 700 mm. Seasonal residuals are much larger spread for INCA, than for all other data sets. However, when comparing those two data sets on a long-term basis, they achieve a high agreement. For example, the sum of precipitation over time reaches similar values. These two data sets also show a high correlation when looking on them on a monthly basis opposed to when comparing them on a daily basis.

According to Kobold und Sušelj (2005, who researched the uncertainty of precipitation forecasts as input into hydrological models in Slovenia, an error in precipitation leads to a 1.6 bigger error in peak discharge. Moreover, an overestimated precipitation sum in winter will lead to higher snow accumulation. Consequently, snow melt will cause larger discharge in spring or summer, depending on the location of the catchment area. When using precipitation data, it is therefore crucial to know the limitations of the data sets, in order to critically handle the impacts on the model (Kobold and Sušelj 2005; Gampe and Ludwig 2017).

- Precipitation has a higher agreement with an increasing catchment area.

Although the variation of the mean annual precipitation shows large discrepancies, they get smaller with a higher catchment area. The best agreement of interannual variability, mean annual precipitation height, etc. between the data sets is therefore found in Golling and in Greimpersdorf. For all data sets the seasonal residuals of precipitation tend to have a smaller distribution of the IQR value in the largest catchment areas.

5.3 Limitations

Several limitations can be found in the approach of this thesis.

- SPARTACUS is used as the data set that the comparison is based on.

The data in SPARTACUS cover the longest time period, however it is still a calculation and the grid data are also just an estimation of reality. As every other model, errors and limitations within the data set can be found. When comparing the data sets, it can be recognised that for example the mean monthly temperature in Mittersill and Golling has a higher agreement to each other than to SPARTACUS. Especially for values, where all other data sets have a small bias between them and a large discrepancy to SPARTACUS, the conclusion can be drawn that SPARTACUS has its limitations.

In chapter 2.1.2 it is stated that Hiebl and Frei (2017) find a general underestimation of precipitation data between a few percent in summer up to several 10%. Looking at the comparisons for precipitation SPARTACUS shows a tendency of less precipitation compared to all other data sets. This can be seen for example when looking on the sum of precipitation over time or the mean annual precipitation height. Especially in Salzburg, where higher elevations can be found, SPARTACUS predicts obviously the smallest precipitation height. As SPARTACUS is the data set that the others are compared to, an overestimation of all other data sets was described in chapter 4. However, considered the findings of Hiebl et al. (2017) this thesis can verify that an underestimation, especially in higher regions, is shown (Hiebl and Frei 2017).

- The comparison is conducted for a limited time period and chosen catchments.

As outlined, the catchments were chosen so that area, location and elevation vary. However, this is still a very small area and as shown the bias for Ybbs and Salzach are different. Consequently, all statements found in this thesis can only be applied for these certain regions in Austria, in the Danube catchment.

- Only the input data sets were researched, without any further processing, concerning the hydrological model.

Raimonet et al. (2017) state in their research that meteorological data need to be evaluated using hydrological models before putting the data as input data into simulations. It is explained that the output of a hydrological model strongly relies on the quality of the precipitation data. Especially, as the precipitation data show larger discrepancies than continuous variables like temperature. As the purpose for the compared data sets is that they are used for hydrological modelling, the outputs to different models should be compared as well, to get better insight on the data sets and to try with which data set the model can be calibrated close enough to the real runoff (Raimonet et al. 2017).

5.4 Recommendation and future prospects

As outlined in chapter 1.1 rain gauges, satellite and radar data are prone to different sources of errors. (Re-)analysis data have potential to work around these errors. Essou et al (2017) show that global (re)analysis data were already successfully used in the USA. The bias that they found was marginal and calibrating the hydrological model was enough to get good results. Essou, et al. (2017) draw the conclusion that (re)analysis data show similar good results as traditional gridded observation data, when used in hydrological models. Gampe and Ludwig (2017) researched different meteorological data sets in the Italian alpine region and come to the conclusion that between various data sets it is important to find the best possible reference precipitation. When looking on all statistic tests in this thesis, it is visible that the data scatter and do not show many regularities. The only data set that should obviously be excluded from further usage is the E-OBS data set, as it shows largely discrepancies to all other data sets in the Ybbs catchment. It is recommended to apply SPARTACUS, INCA and COSMO-REA6 as input data for a hydrological model in the research area and compare the output again. This offers the opportunity to see how sensitive the model changes according to the precipitation data, and with which data set the model can be calibrated best (Essou, Brissette, and Lucas-Picher 2017; Gampe and Ludwig 2017).

As SPARTACUS and INCA have the highest spatial resolution and Austria shows a complex topography and different small-scale processes, those data sets are likely to represent the local patterns best. On the other hand, the large spatial coverage of COSMO-REA6 can be of high importance for the international Clim2Power-project and therefore further focus should be put on COSMO-REA6 as well (Essou, Brissette, and Lucas-Picher 2017; Gampe and Ludwig 2017).

As the data scatter so highly, this thesis outlines that a comparison of the data sets is important before using them in a hydrological model. Looking on the results and interpretation, it is obvious that the catchments and data sets must be researched individually, and general differences can hardly be found. This thesis provides potential information for the input data and possible explanation on the output of hydrological models.

6. List of Figures

7. List of Tables

8. List of Equations

9. References

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10. Appendix

10.1 Frequency of meteorological events for temperature – Salzach

The colours found in Table 10-1 to Table 10-4 represent the following:

Orange: value of the data set is bigger than predicted by SPARTACUS
Green: value of the data set is the same as predicted by SPARTACUS
Blue: value of the data set is smaller than predicted by SPARTACUS

Table 10-1: Defined events of temperature – Salzach

Subcatchment	Frost days (Tmean<=0°C)				Warm Days (Tmean>=13°C)			
	SPAR-TACUS	INCA	COSMO-REA6	E-OBS	SPAR-TACUS	INCA	COSMO-REA6	E-OBS
Sulzau, 2003	174	184	181	162	23	15	14	32
Sulzau, 2004	162	179	178	158	2	0	0	2
Sulzau, 2005	155	170	169	149	7	3	2	12
Sulzau, 2006	153	168	171	152	11	7	3	14
Sulzau, 2007	160	173	178	159	9	7	5	9
Sulzau, 2008	181	186	185	181	3	0	0	2
Sulzau, 2009	160	168	167	156	9	5	2	6
Sulzau, 2010	176	185	186	173	17	13	5	14
Sulzau, 2011	138	160	152	139	11	10	11	10
Sulzau, 2012	156	158	169	160	15	13	10	10
Sulzau, 2013	174	184	172	174	18	14	11	14
Sulzau, 2014	135	139	145	145	6	4	1	3
Sulzau, 2015	144	162	157	150	29	22	20	24
Mittersill, 2003	138	150	153	144	65	45	51	54
Mittersill, 2004	135	149	146	140	31	18	20	21
Mittersill, 2005	131	139	137	132	29	20	19	25
Mittersill, 2006	123	132	135	132	47	31	33	35
Mittersill, 2007	125	139	151	137	27	12	13	11
Mittersill, 2008	131	140	152	148	38	15	29	20
Mittersill, 2009	135	143	141	146	38	32	32	22
Mittersill, 2010	145	153	153	151	39	27	26	22
Mittersill, 2011	101	118	119	120	32	26	27	18
Mittersill, 2012	118	134	139	141	45	30	36	23
Mittersill, 2013	129	153	147	158	42	29	28	23
Mittersill, 2014	96	109	113	126	25	12	12	7
Mittersill, 2015	108	128	124	125	49	42	46	39
Golling, 2003	112	132	131	124	98	70	81	77
Golling, 2004	115	130	125	114	51	35	41	35
Golling, 2005	119	123	122	121	52	38	43	35
Golling, 2006	110	120	119	114	65	48	56	53
Golling, 2007	96	113	123	105	54	31	49	37
Golling, 2008	104	125	124	121	67	46	56	44
Golling, 2009	115	126	128	132	66	47	54	45
Golling, 2010	119	131	127	129	55	43	45	40
Golling, 2011	79	104	97	107	62	39	48	35

Golling, 2012	100	110	109	109	74	52	59	48
Golling, 2013	108	125	123	136	61	43	50	41
Golling, 2014	61	81	84	95	52	27	32	23
Golling, 2015	84	102	101	105	68	58	62	55

10.2 Frequency of meteorological events for precipitation – Salzach

Table 10-2: Defined events of precipitation – Salzach

Subcatchment	Dry Days (P<=0.1mm/day)				Days with High Precipitation (P>=20mm/day)			
	SPAR-TACUS	INCA	COSMO-REA6	E-OBS	SPAR-TACUS	INCA	COSMO-REA6	E-OBS
Sulzau, 2003	183	167	158	182	18	17	19	14
Sulzau, 2004	152	150	137	151	16	27	20	15
Sulzau, 2005	156	147	136	166	22	36	31	21
Sulzau, 2006	165	152	148	71	18	27	20	11
Sulzau, 2007	172	145	136	160	26	30	23	12
Sulzau, 2008	154	140	113	151	23	33	25	24
Sulzau, 2009	139	149	121	150	20	23	19	22
Sulzau, 2010	136	145	109	146	18	29	25	15
Sulzau, 2011	173	176	166	185	22	32	25	18
Sulzau, 2012	141	132	120	161	26	42	26	22
Sulzau, 2013	132	101	115	162	24	22	25	22
Sulzau, 2014	119	142	115	155	21	17	20	27
Sulzau, 2015	176	201	153	189	19	17	16	13
Mittersill, 2003	180	168	156	183	15	15	21	14
Mittersill, 2004	151	149	130	151	11	21	15	15
Mittersill, 2005	156	149	129	164	19	29	25	19
Mittersill, 2006	167	147	148	175	15	22	17	13
Mittersill, 2007	170	135	132	162	19	25	20	12
Mittersill, 2008	155	138	111	155	16	26	22	20
Mittersill, 2009	143	146	112	150	19	19	18	20
Mittersill, 2010	135	143	111	146	15	19	22	16
Mittersill, 2011	181	177	164	186	19	24	23	18
Mittersill, 2012	142	133	115	161	16	25	23	20
Mittersill, 2013	141	109	116	163	22	19	22	22
Mittersill, 2014	124	145	112	158	16	16	19	24
Mittersill, 2015	166	194	137	191	10	6	14	13
Golling, 2003	164	153	146	174	15	12	16	20
Golling, 2004	128	127	116	139	10	15	13	15
Golling, 2005	125	123	114	153	19	21	25	18
Golling, 2006	136	129	131	161	15	16	16	13
Golling, 2007	139	122	121	149	17	20	16	12
Golling, 2008	122	114	99	142	15	13	17	21
Golling, 2009	117	118	97	137	15	15	21	21
Golling, 2010	120	125	92	142	13	15	16	14
Golling, 2011	165	166	151	184	15	14	18	18
Golling, 2012	125	112	103	152	18	19	20	21
Golling, 2013	116	92	103	143	17	23	23	23
Golling, 2014	111	113	102	138	12	15	18	20
Golling, 2015	143	163	137	184	13	13	11	15

10.3 Frequency of meteorological events for temperature – Ybbs

Table 10-3: Defined events temperature – Ybbs

Subcatchment	Frost days (Tmean<=0°C)				Warm Days (Tmean>=13°C)			
	SPARTA-CUS	INCA	COSMO-REA6	E-OBS	SPAR-TACUS	INCA	COSMO-REA6	E-OBS
Opponitz, 2003	90	91	75	79	121	121	132	127
Opponitz, 2004	97	97	88	86	84	79	104	96
Opponitz, 2005	103	108	99	90	89	85	103	103
Opponitz, 2006	92	94	83	79	98	82	112	111
Opponitz, 2007	54	59	55	35	99	82	110	106
Opponitz, 2008	70	69	46	47	101	91	107	104
Opponitz, 2009	75	82	77	67	109	95	119	122
Opponitz, 2010	94	99	91	92	85	71	89	98
Opponitz, 2011	63	62	48	57	108	85	120	131
Opponitz, 2012	70	81	69	56	105	93	117	116
Opponitz, 2013	90	93	78	84	96	85	110	108
Opponitz, 2014	25	30	16	26	97	85	116	111
Opponitz, 2015	59	75	55	43	101	88	118	113
Greimpersdorf, 2003	65	79	74	71	143	127	138	131
Greimpersdorf, 2004	72	86	85	83	124	100	121	110
Greimpersdorf, 2005	84	96	95	83	128	107	121	116
Greimpersdorf, 2006	75	86	83	71	134	102	131	120
Greimpersdorf, 2007	32	44	40	32	138	104	126	122
Greimpersdorf, 2008	36	54	38	38	127	109	123	114
Greimpersdorf, 2009	51	67	62	55	148	114	147	135
Greimpersdorf, 2010	79	91	87	84	132	89	112	110
Greimpersdorf, 2011	44	57	46	52	152	120	140	144
Greimpersdorf, 2012	46	62	56	47	140	113	135	136
Greimpersdorf, 2013	60	84	75	70	137	103	123	119
Greimpersdorf, 2014	16	18	15	23	147	105	140	130
Greimpersdorf, 2015	29	49	41	30	138	111	128	124
Krenstetten, 2003	60	68	66	61	146	136	150	143
Krenstetten, 2004	64	63	70	57	135	123	142	128
Krenstetten, 2005	78	82	84	75	134	129	133	132
Krenstetten, 2006	69	77	82	64	148	129	148	147
Krenstetten, 2007	30	32	31	28	146	134	146	143
Krenstetten, 2008	32	37	31	28	130	126	136	131
Krenstetten, 2009	50	54	51	45	164	146	166	164
Krenstetten, 2010	78	81	82	74	133	118	138	131
Krenstetten, 2011	41	56	48	42	159	149	160	151
Krenstetten, 2012	42	44	46	40	144	136	148	149
Krenstetten, 2013	54	65	66	55	141	130	141	145
Krenstetten, 2014	17	19	16	17	158	143	169	156
Krenstetten, 2015	23	31	29	18	141	133	149	149

10.4 Frequency of meteorological events for precipitation – Ybbs

Table 10-4: Defined events of precipitation – Ybbs

Subcatchment	Dry Days (P<=0.1mm/day)				Days with High Precipitation (P>=20mm/day)			
	SPAR-TACUS	INCA	COSMO-REA6	E-OBS	SPAR-TACUS	INCA	COSMO-REA6	E-OBS
Opponitz, 2003	183	173	176	231	13	11	10	4
Opponitz, 2004	144	143	149	199	17	18	13	3
Opponitz, 2005	138	144	141	195	29	29	21	6
Opponitz, 2006	151	147	131	204	26	23	22	5
Opponitz, 2007	146	135	142	196	23	17	24	7
Opponitz, 2008	151	152	144	188	24	23	24	4
Opponitz, 2009	135	136	120	179	32	32	35	11
Opponitz, 2010	127	131	130	192	21	18	17	7
Opponitz, 2011	179	164	178	223	22	20	12	6
Opponitz, 2012	150	143	140	192	19	22	27	3
Opponitz, 2013	139	103	147	189	27	34	21	5
Opponitz, 2014	152	143	149	180	17	26	21	9
Opponitz, 2015	169	170	160	221	18	13	13	5
Greimpersdorf, 2003	192	175	176	174	7	8	5	4
Greimpersdorf, 2004	160	138	147	188	8	12	6	2
Greimpersdorf, 2005	162	141	142	194	15	15	11	5
Greimpersdorf, 2006	168	152	149	193	13	15	14	4
Greimpersdorf, 2007	165	133	138	190	10	15	14	5
Greimpersdorf, 2008	158	150	145	191	9	14	13	4
Greimpersdorf, 2009	150	135	128	174	16	25	23	9
Greimpersdorf, 2010	162	132	128	187	9	13	11	8
Greimpersdorf, 2011	190	143	178	217	9	12	9	6
Greimpersdorf, 2012	160	152	142	190	8	15	15	4
Greimpersdorf, 2013	159	106	145	187	19	30	14	6
Greimpersdorf, 2014	173	144	148	177	11	23	12	7
Greimpersdorf, 2015	180	169	158	216	4	7	6	4
Krenstetten, 2003	190	189	203	224	5	7	3	4
Krenstetten, 2004	164	155	176	188	7	10	6	2
Krenstetten, 2005	162	148	175	192	14	14	5	3
Krenstetten, 2006	179	157	159	194	6	13	7	5
Krenstetten, 2007	169	138	151	184	9	12	11	5
Krenstetten, 2008	162	163	160	195	6	11	8	4
Krenstetten, 2009	155	141	151	181	11	15	11	6
Krenstetten, 2010	166	131	148	189	7	9	6	5
Krenstetten, 2011	198	135	199	221	9	12	7	4
Krenstetten, 2012	163	161	173	187	9	7	6	5
Krenstetten, 2013	164	123	156	196	18	22	8	7
Krenstetten, 2014	182	169	166	188	8	15	10	5
Krenstetten, 2015	193	171	192	211	8	4	3	2

10.5 Mean monthly temperature – Salzach

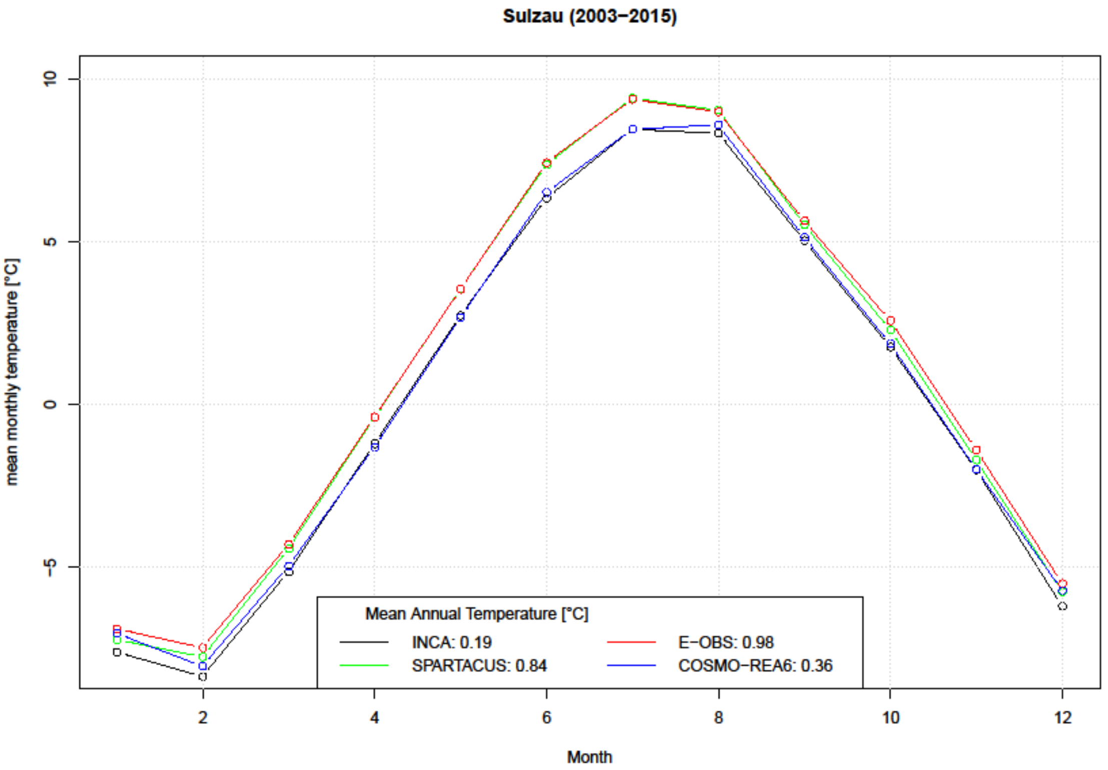

Figure 10-1: Mean monthly temperature – Sulzau

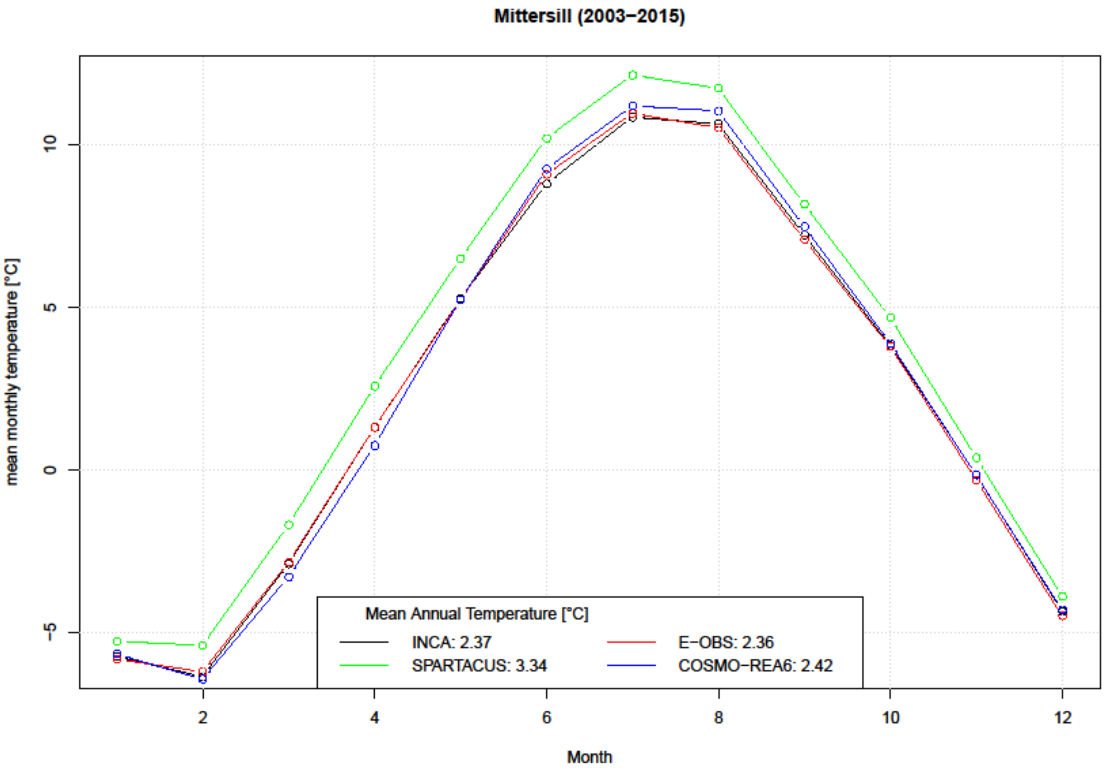

Figure 10-2: Mean monthly temperature – Mittersill

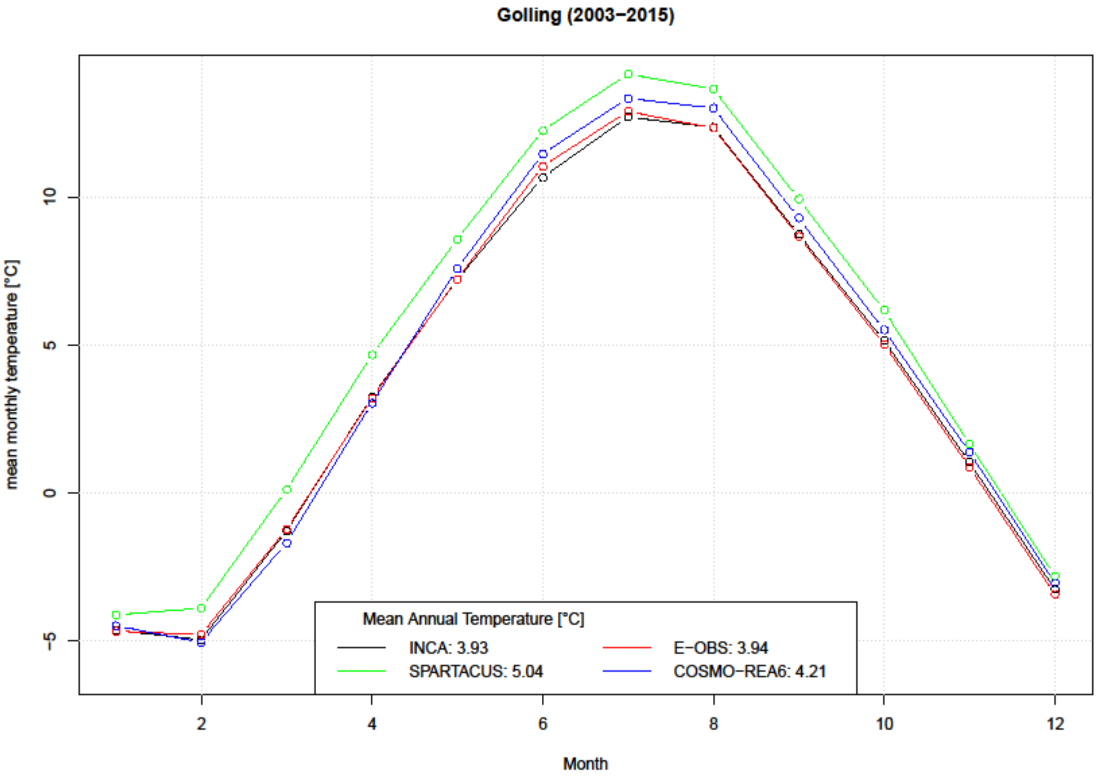

Figure 10-3: Mean monthly temperature – Golling

10.6 Mean monthly temperature – Ybbs

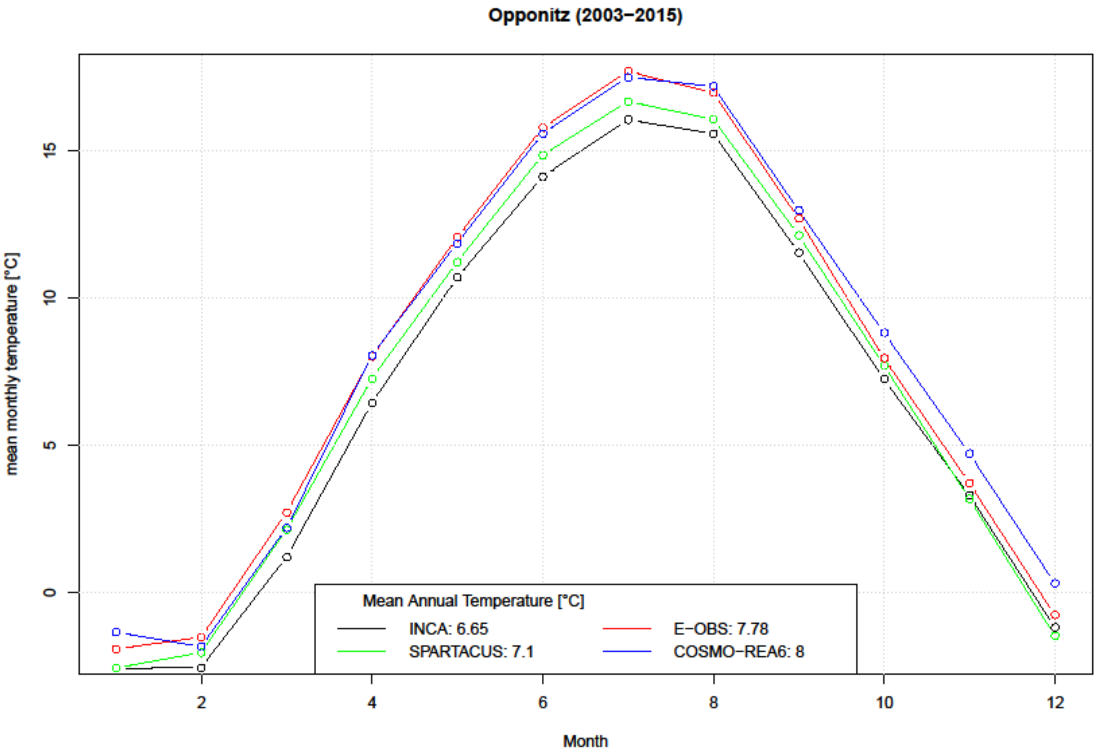

Figure 10-4: Mean monthly temperature – Opponitz

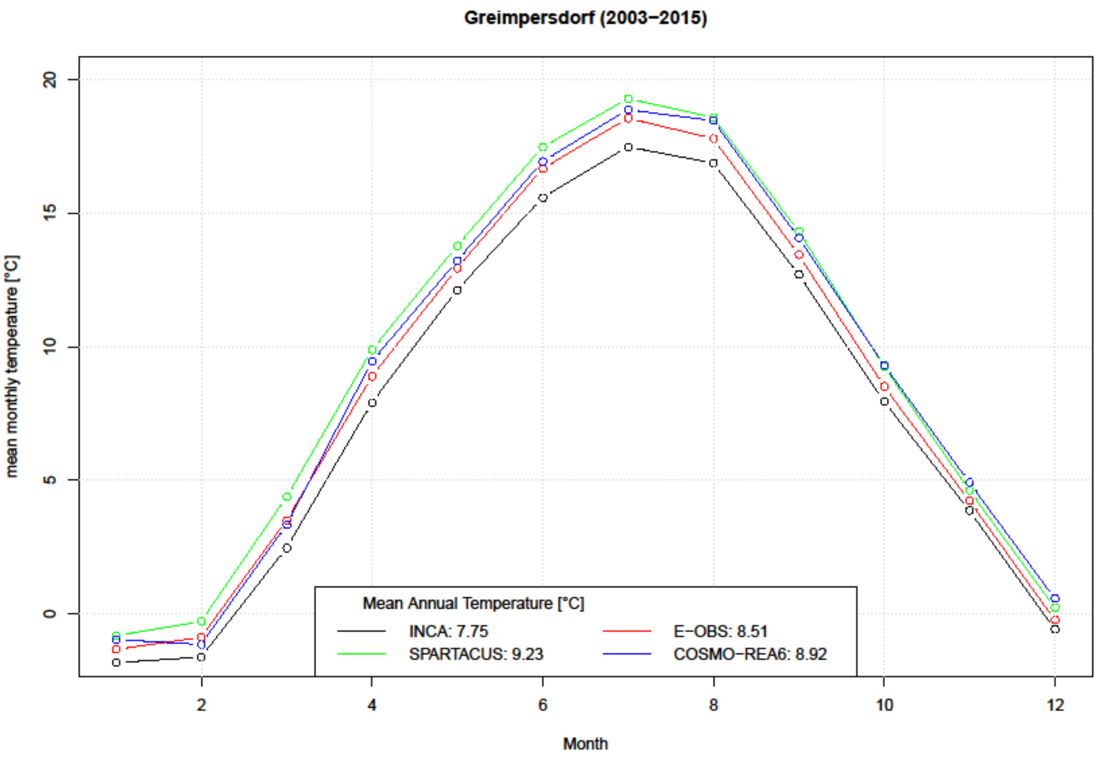

Figure 10-5: Mean monthly temperature – Greimpersdorf

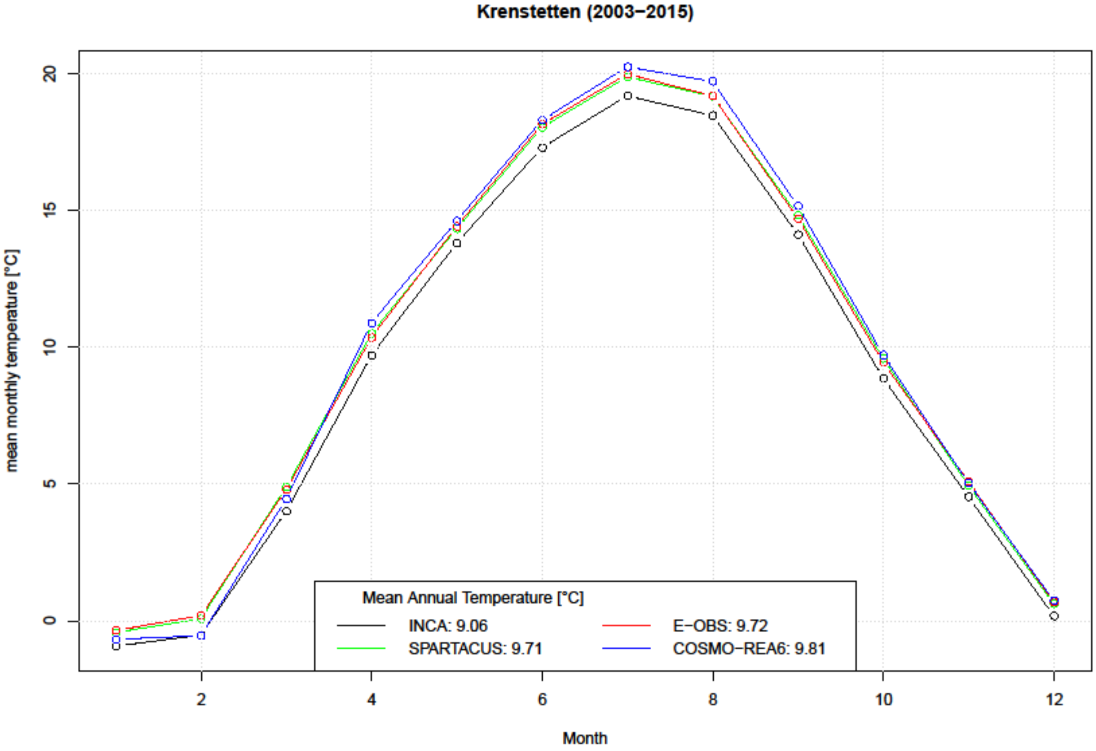

Figure 10-6: Mean monthly temperature – Krenstetten

10.7 Mean annual temperature – Salzach

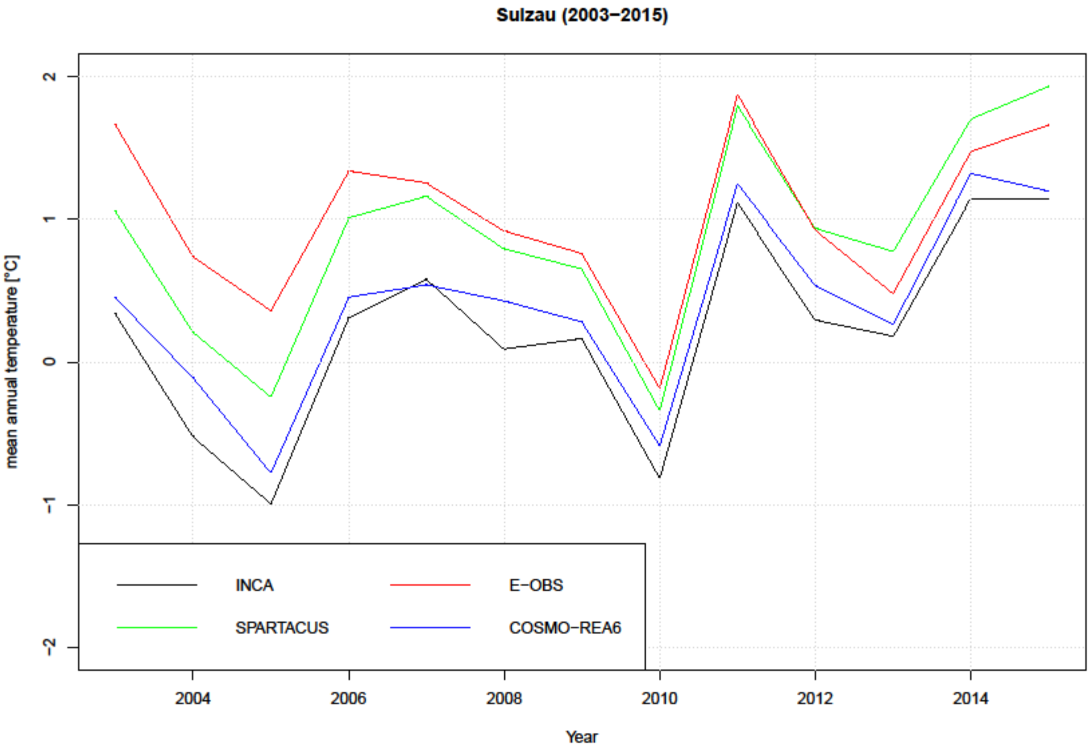

Figure 10-7: Mean annual temperature – Sulzau

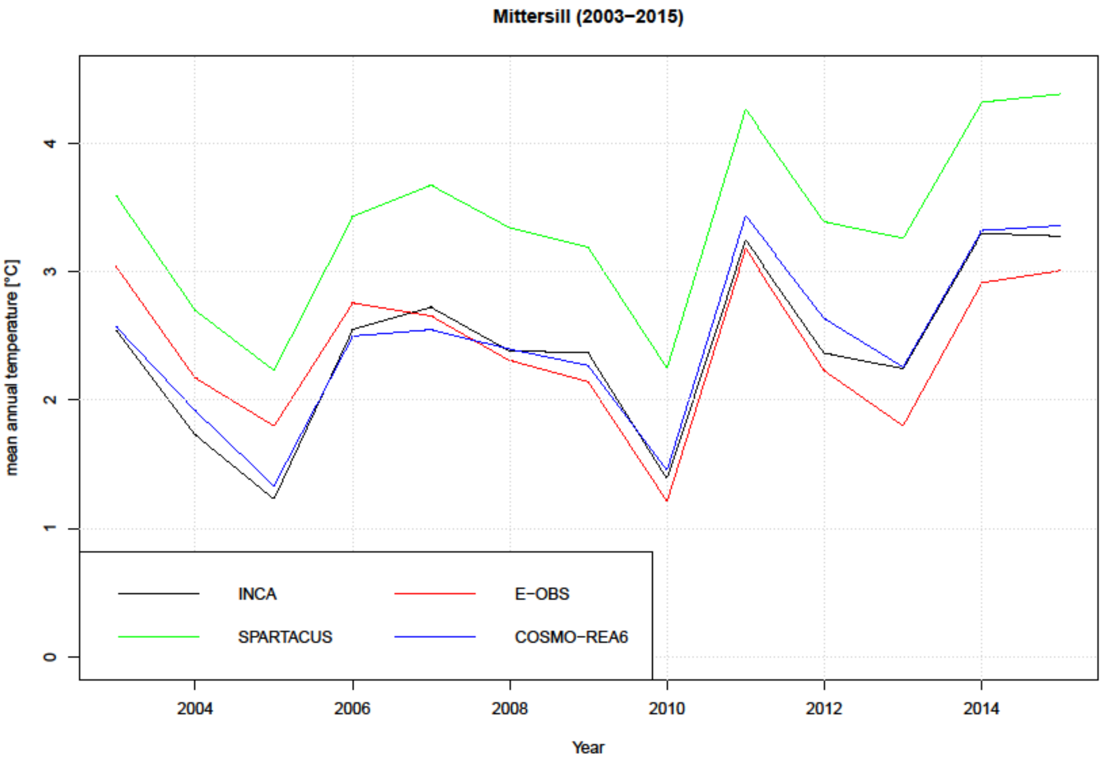

Figure 10-8: Mean annual temperature – Mittersill

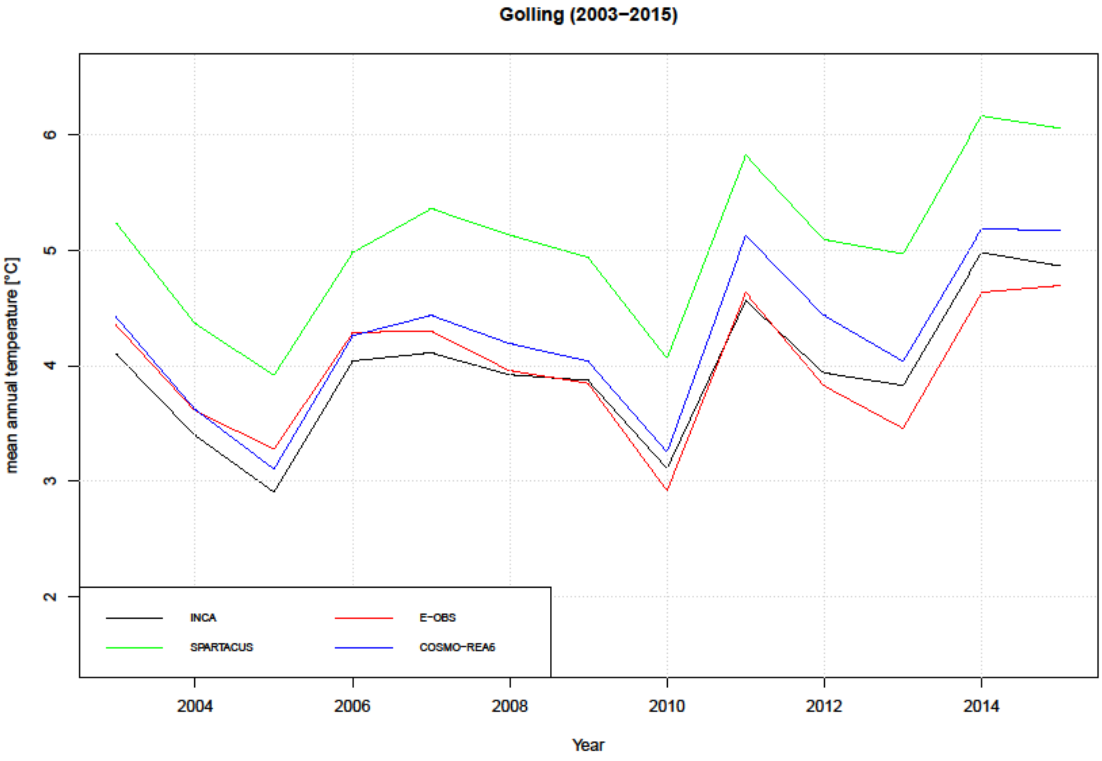

Figure 10-9: Mean annual temperature – Golling

10.8 Mean annual temperature – Ybbs

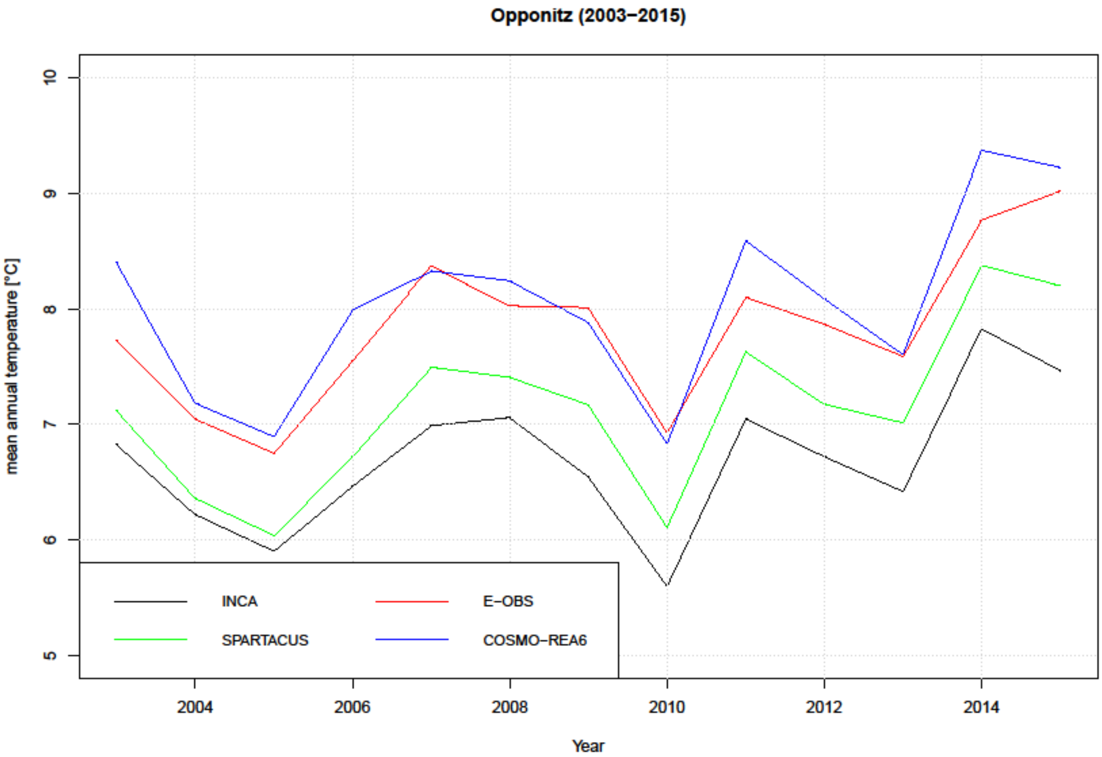

Figure 10-10: Mean annual temperature – Opponitz

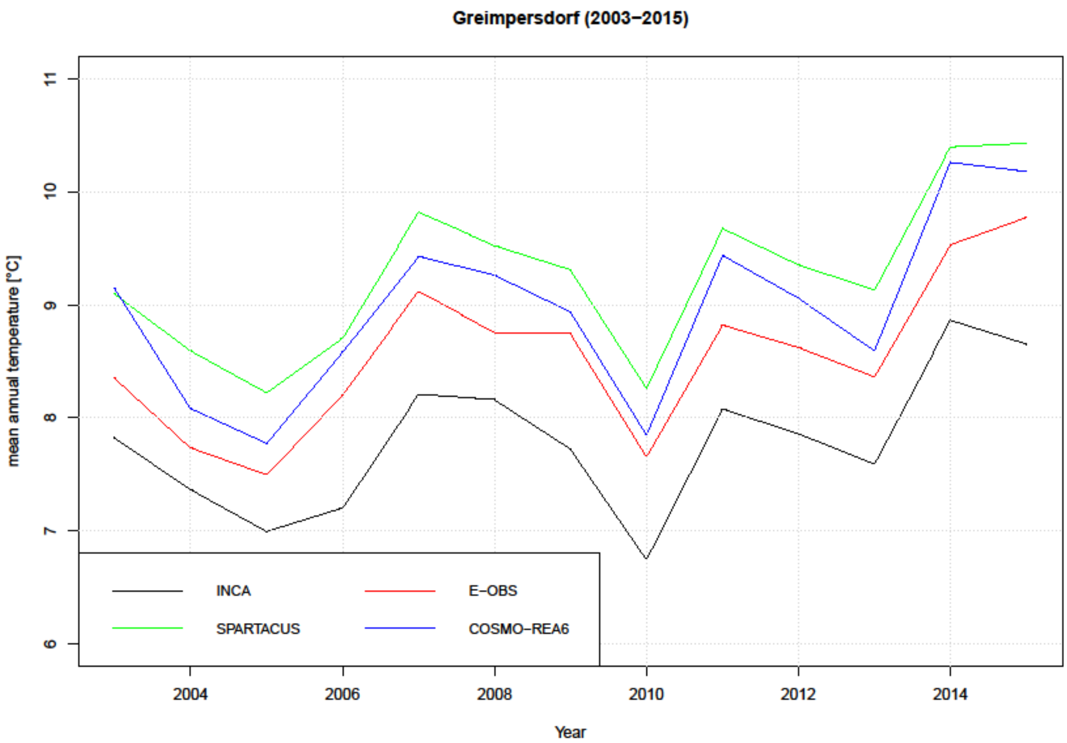

Figure 10-11: Mean annual temperature – Greimpersdorf

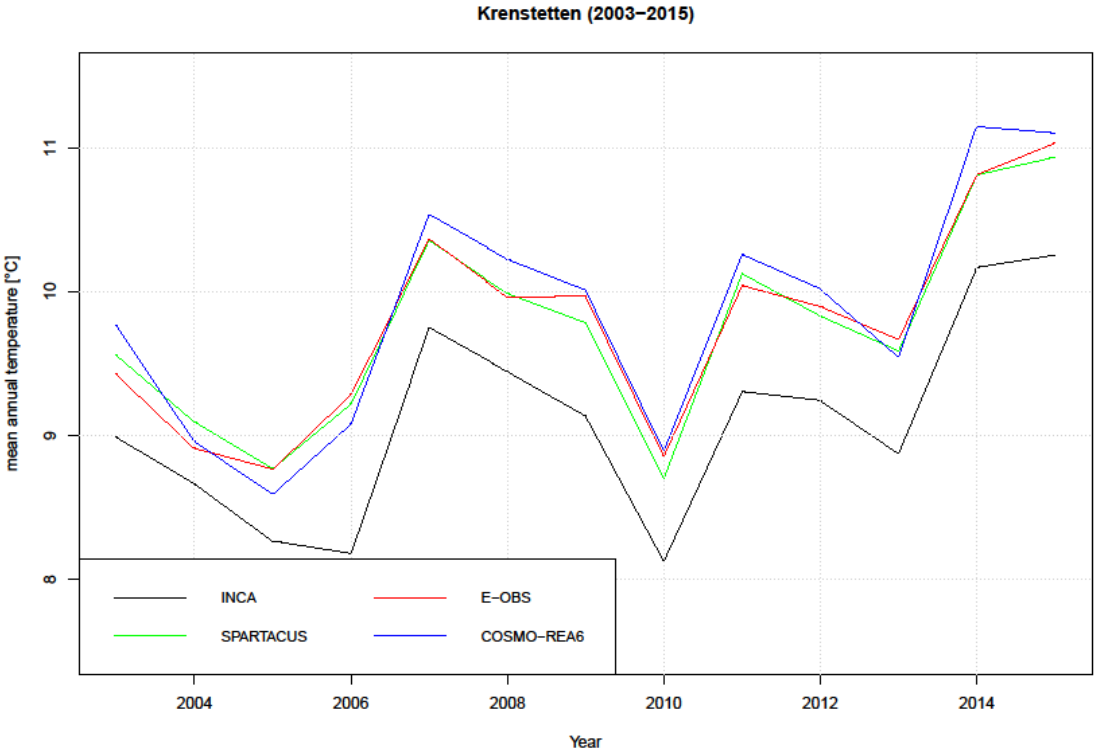

Figure 10-12: Mean annual temperature – Krenstetten

10.9 Mean monthly precipitation height – Salzach

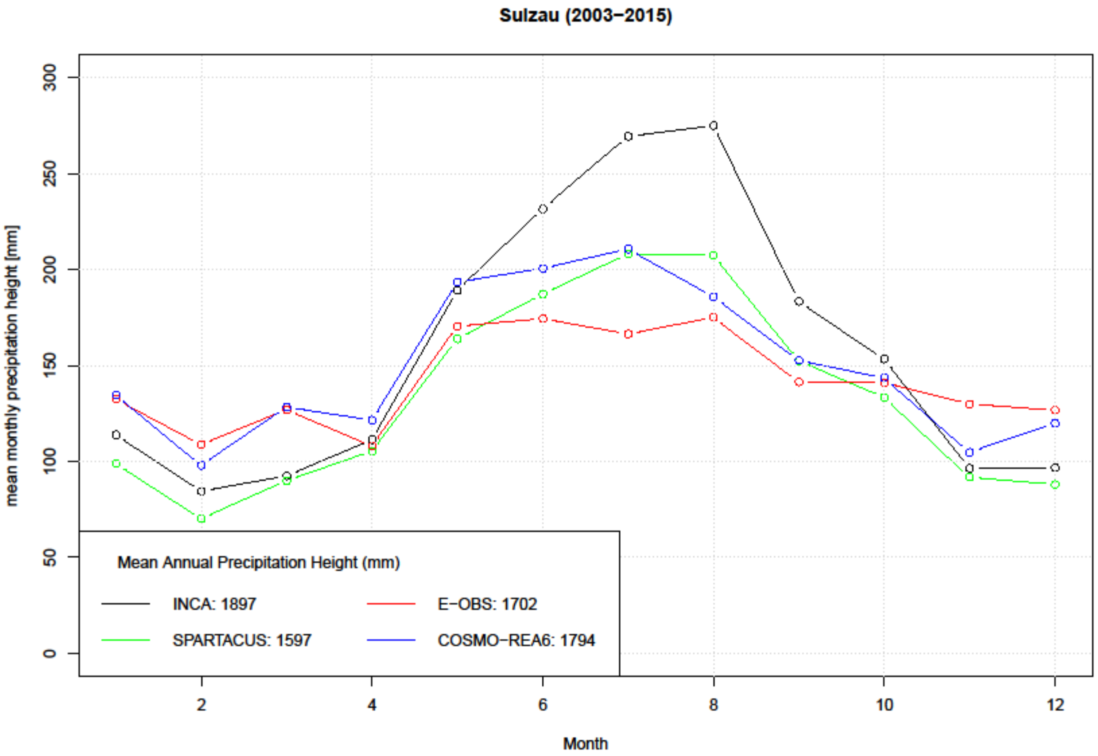

Figure 10-13: Mean monthly precipitation height – Sulzau

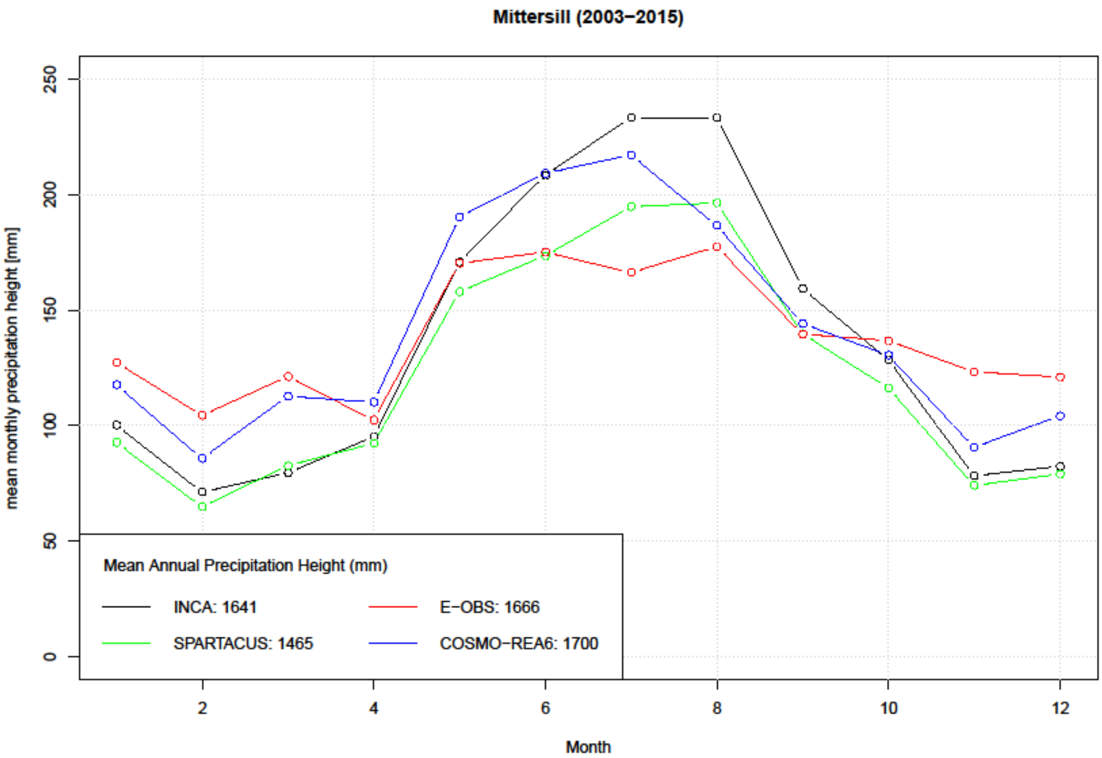

Figure 10-14: Mean monthly precipitation height – Mittersill

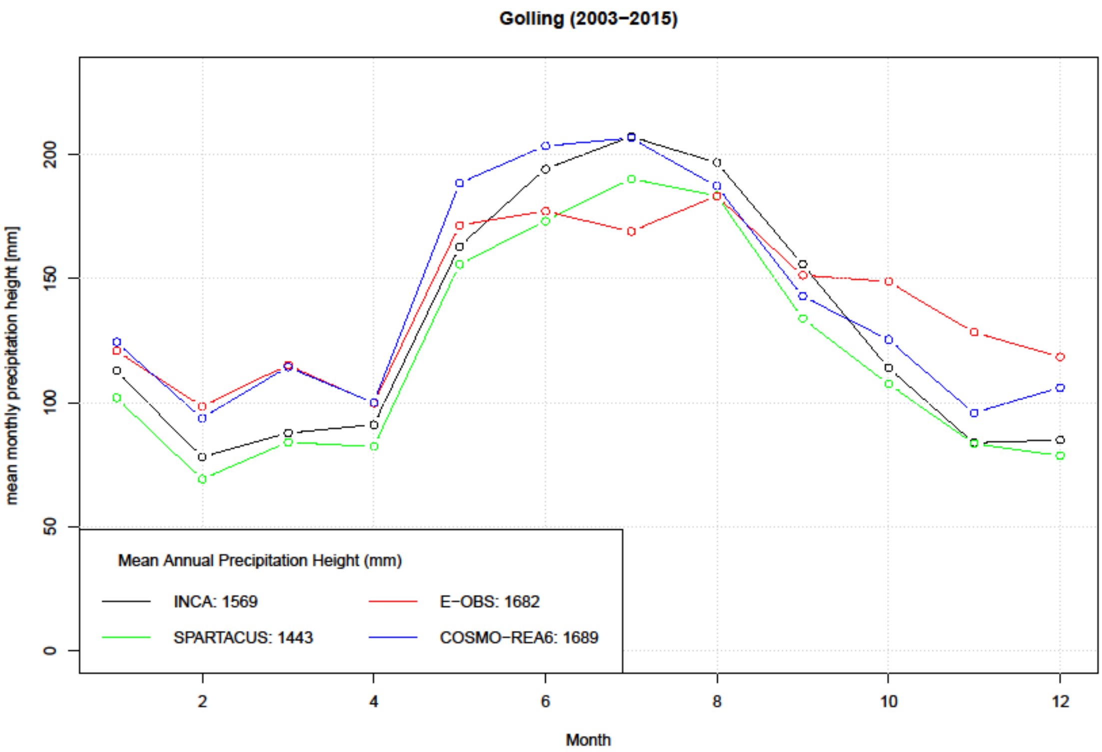

Figure 10-15: Mean monthly precipitation height – Golling

10.10 Mean monthly precipitation height – Ybbs

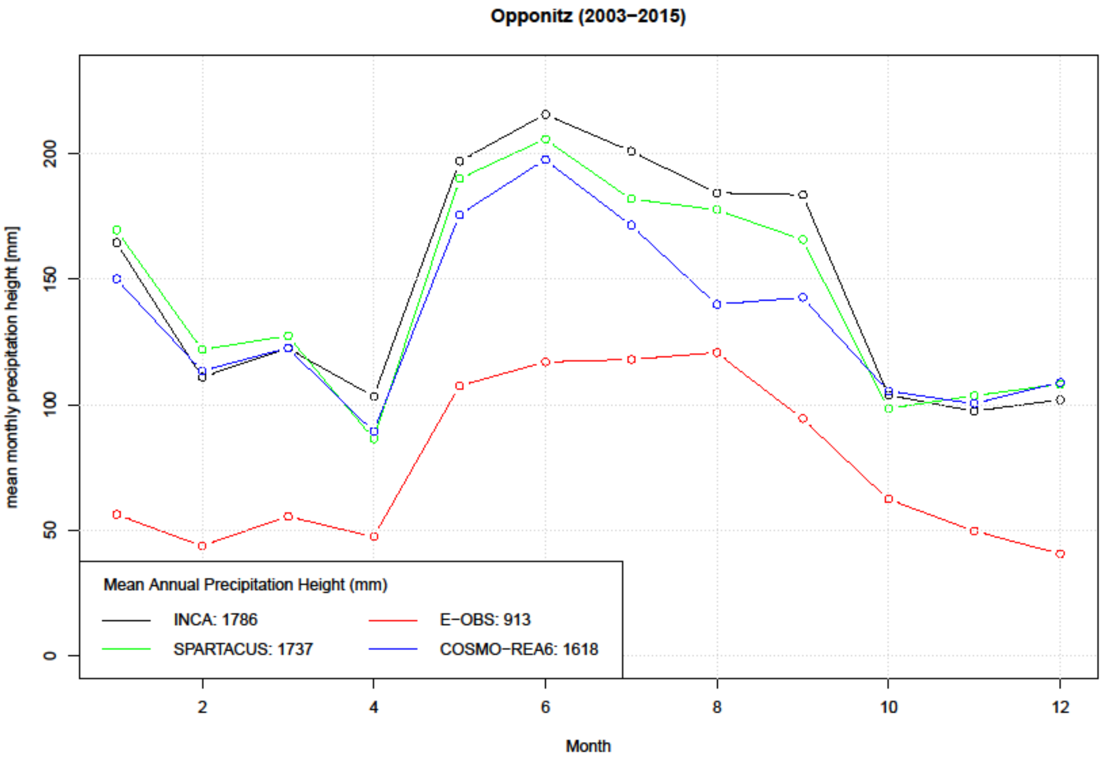

Figure 10-16: Mean monthly precipitation height – Opponitz

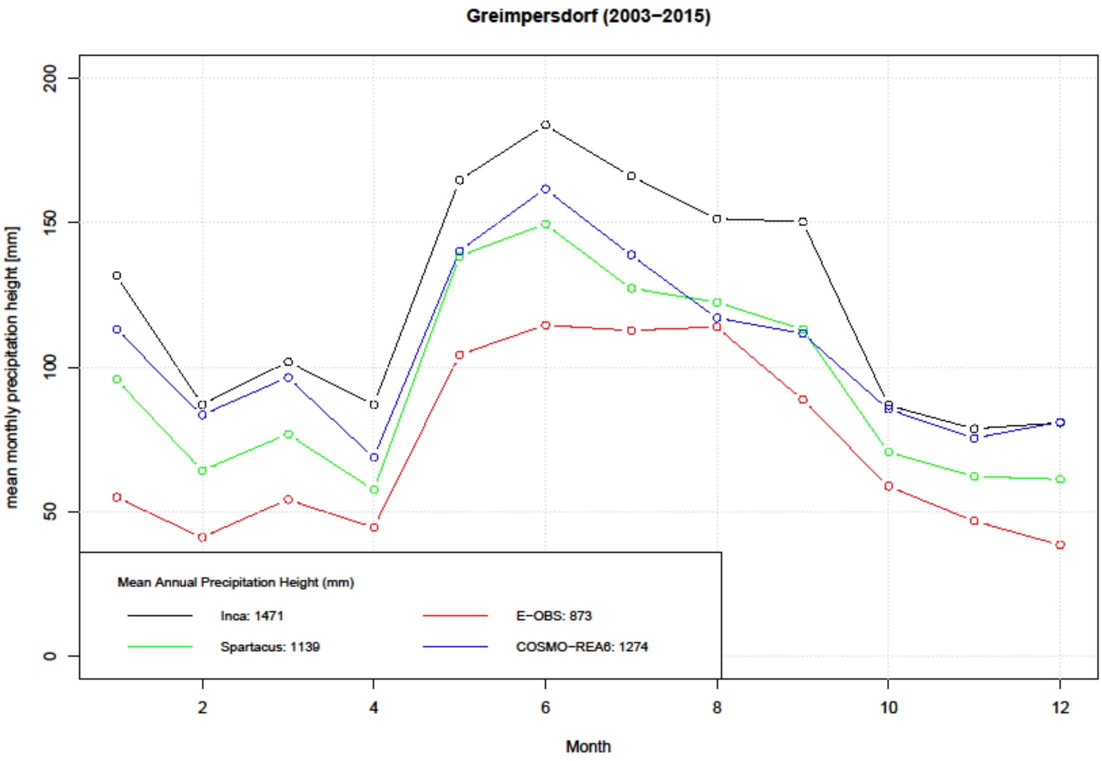

Figure 10-17: Mean monthly precipitation height – Greimpersdorf

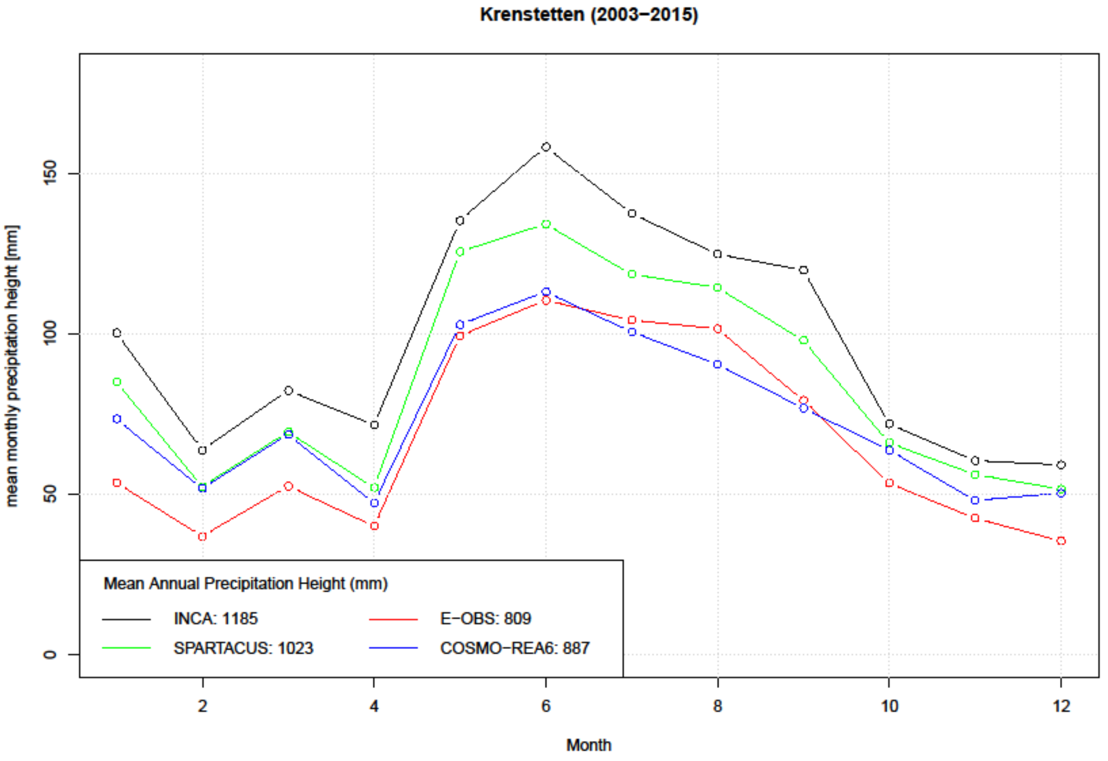

Figure 10-18: Mean monthly precipitation height – Krenstetten

10.11 Mean annual precipitation height – Salzach

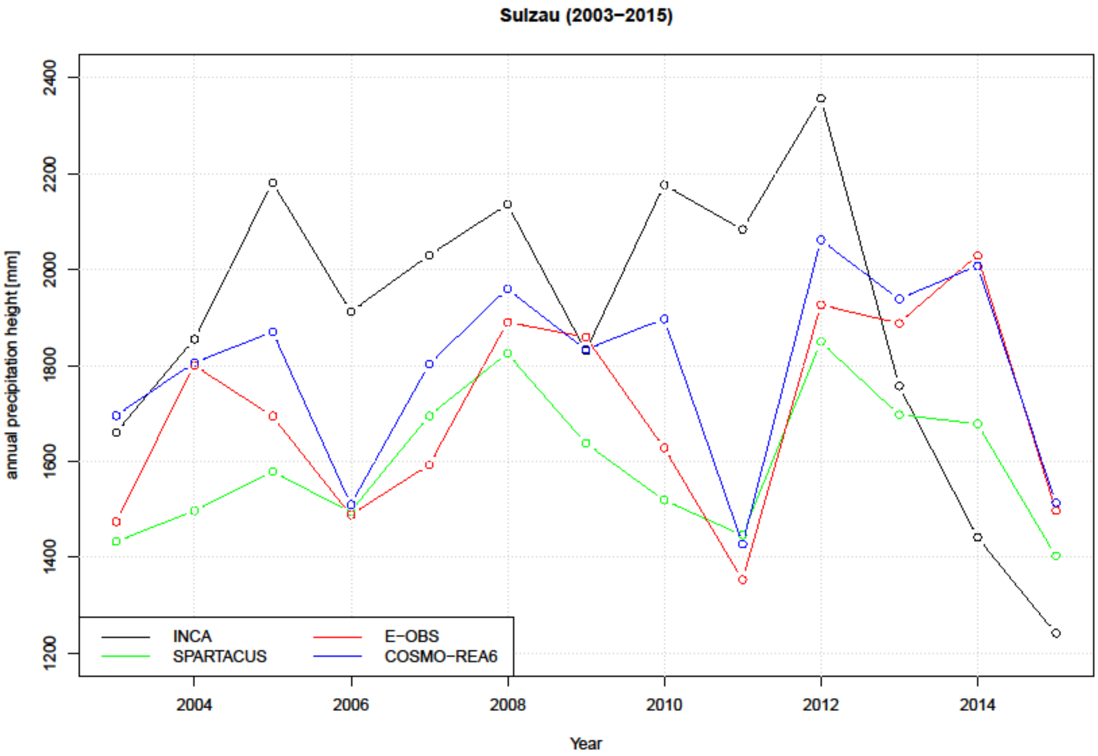

Figure 10-19: Mean annual precipitation height – Sulzau

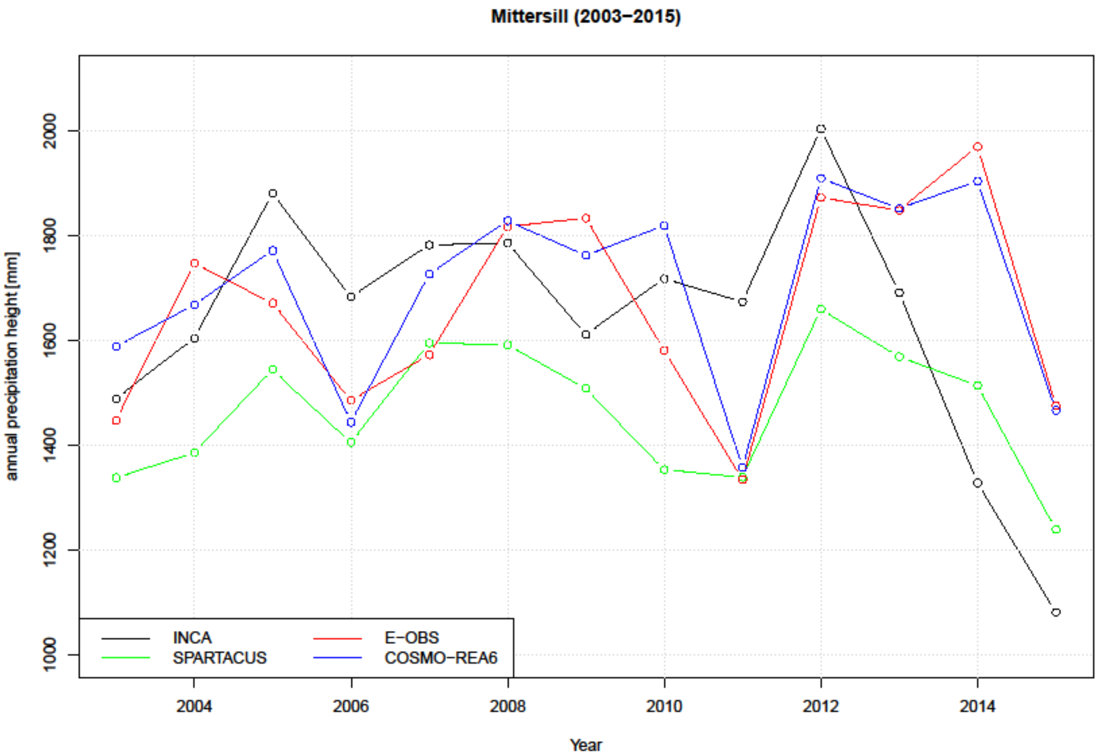

Figure 10-20: Mean annual precipitation height – Mittersill

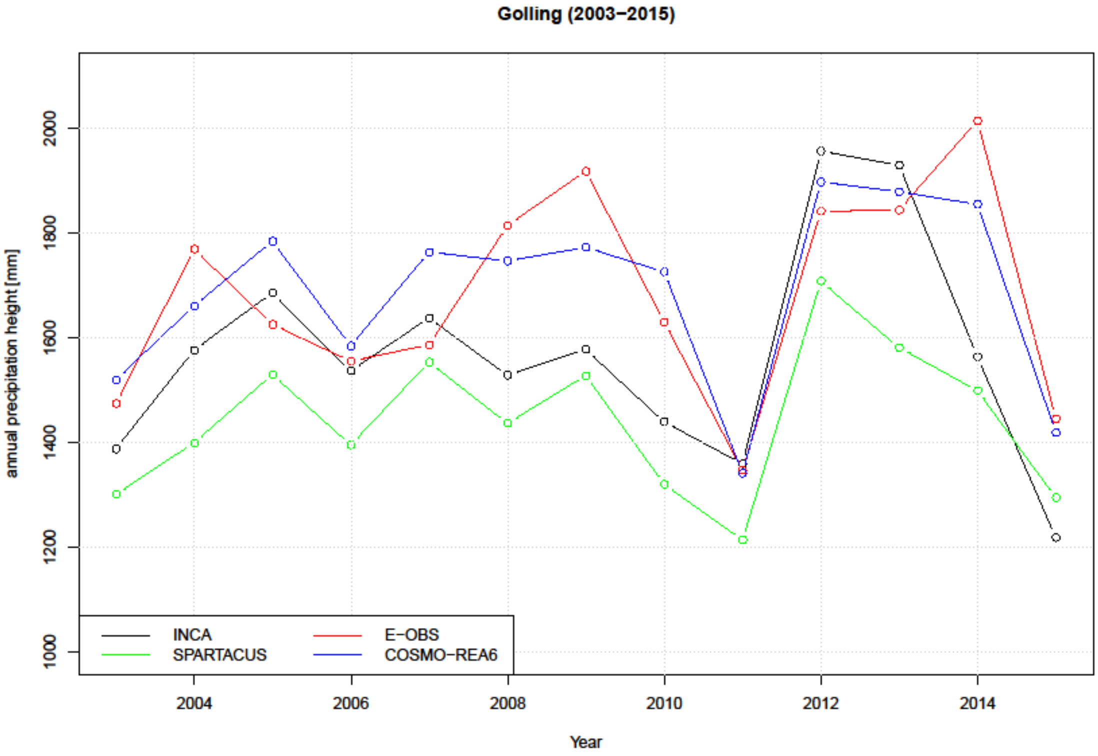

Figure 10-21: Mean annual precipitation height – Golling

10.12 Mean annual precipitation height – Ybbs

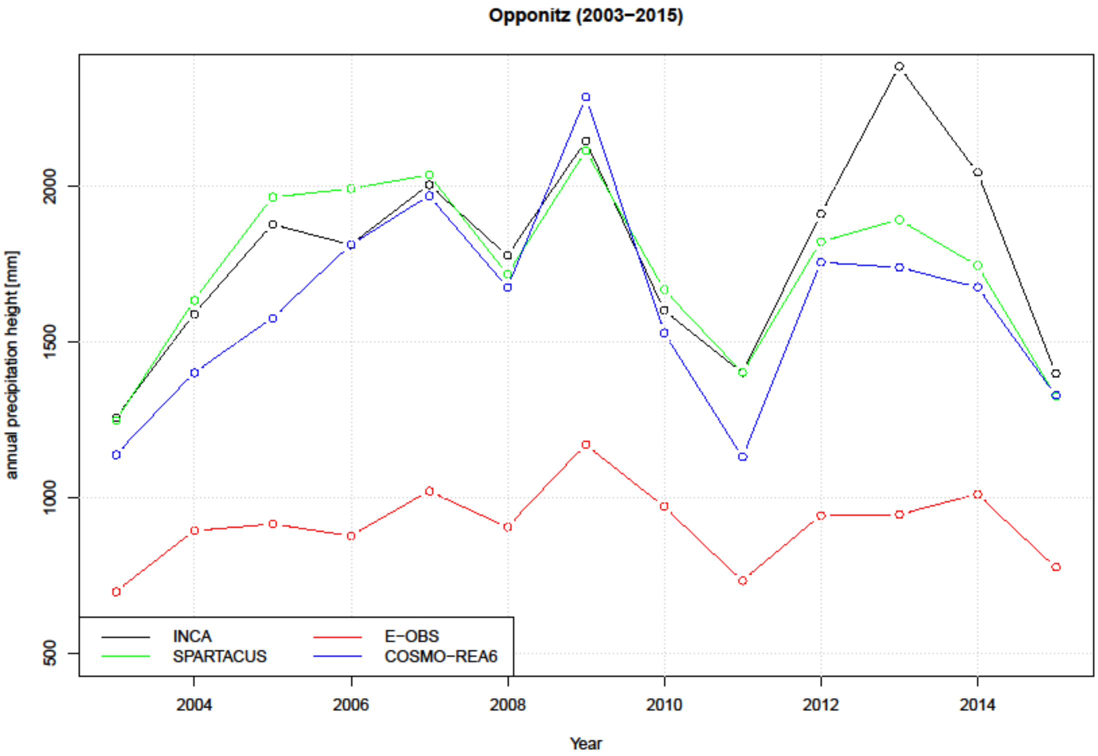

Figure 10-22: Mean annual precipitation height – Opponitz

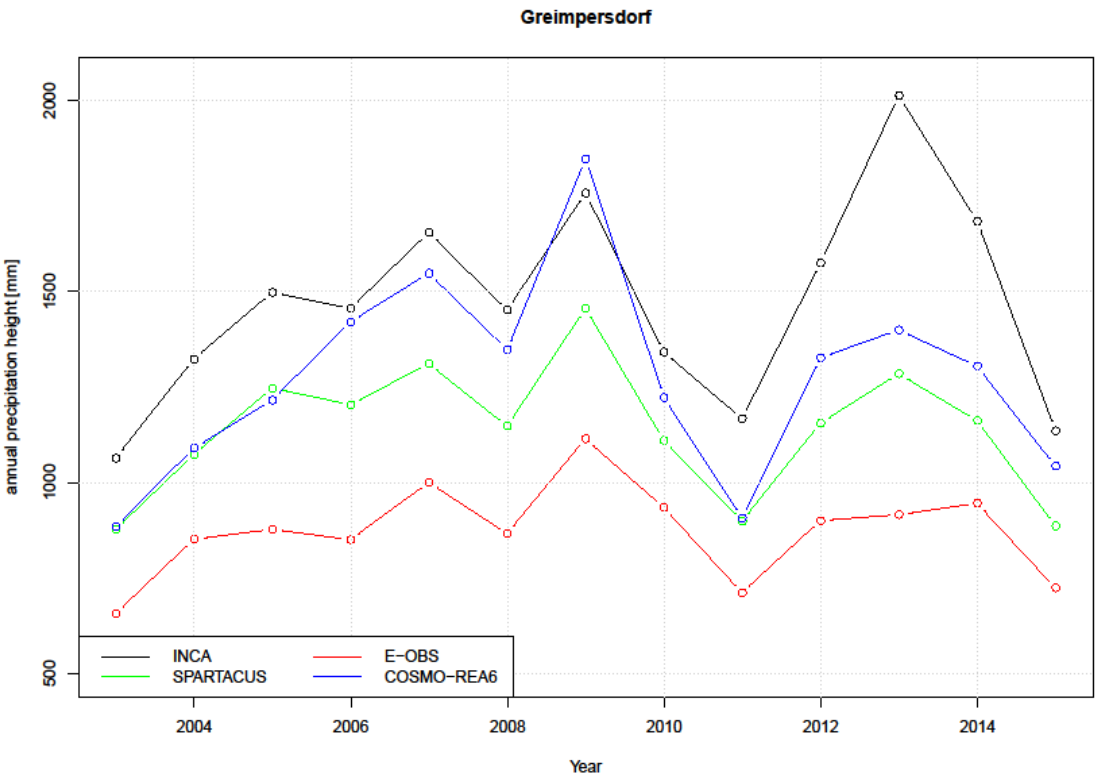

Figure 10-23: Mean annual precipitation height – Greimpersdorf

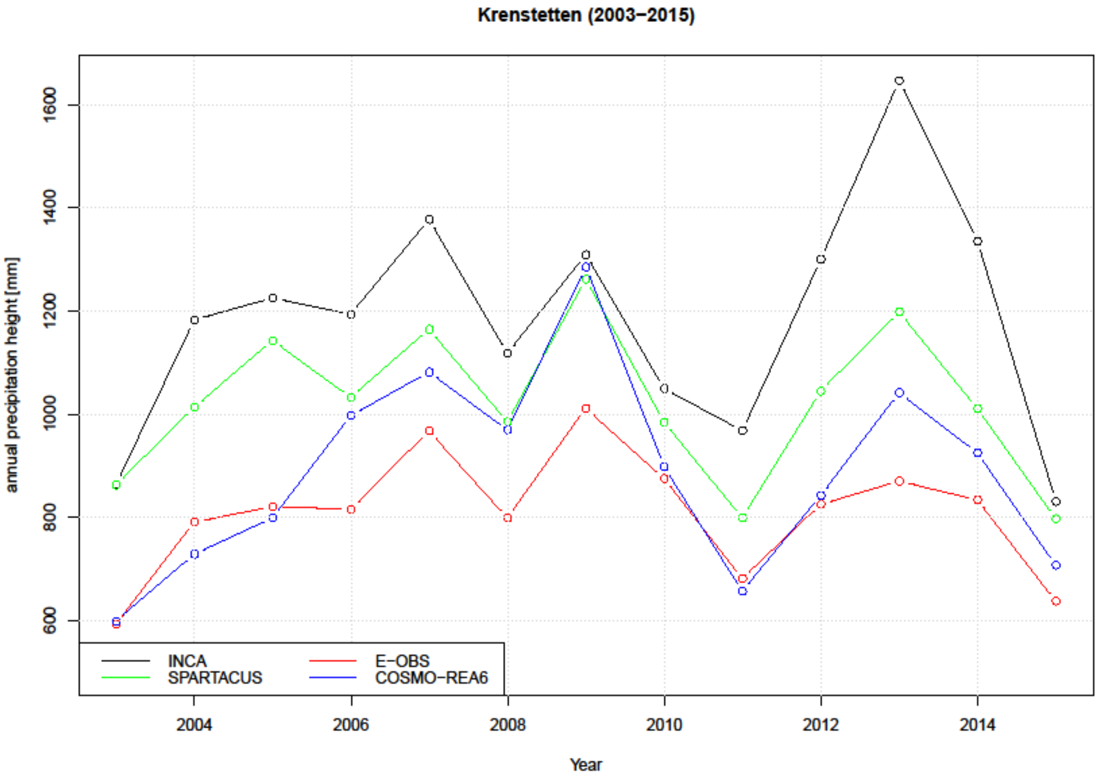

Figure 10-24: Mean annual precipitation height – Krenstetten

10.13 Sum of precipitation over time – Salzach

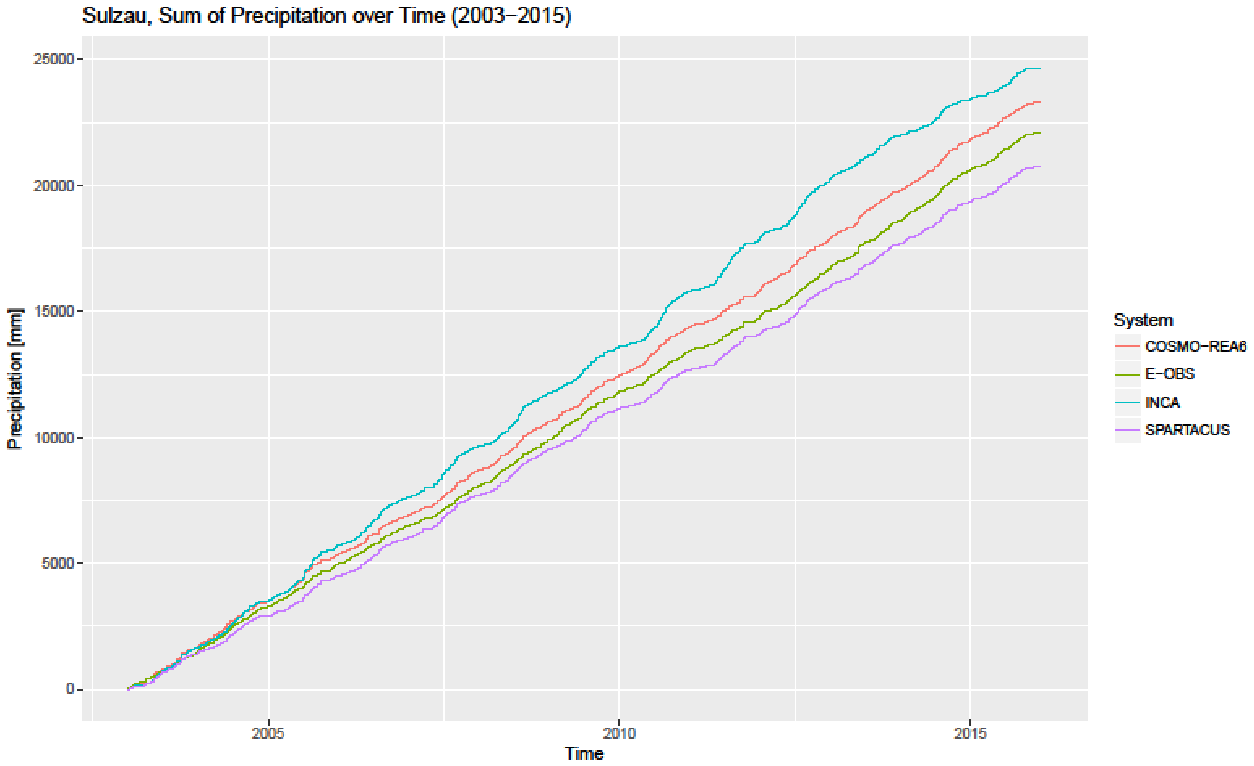

Figure 10-25: Sum of precipitation over time – Sulzau

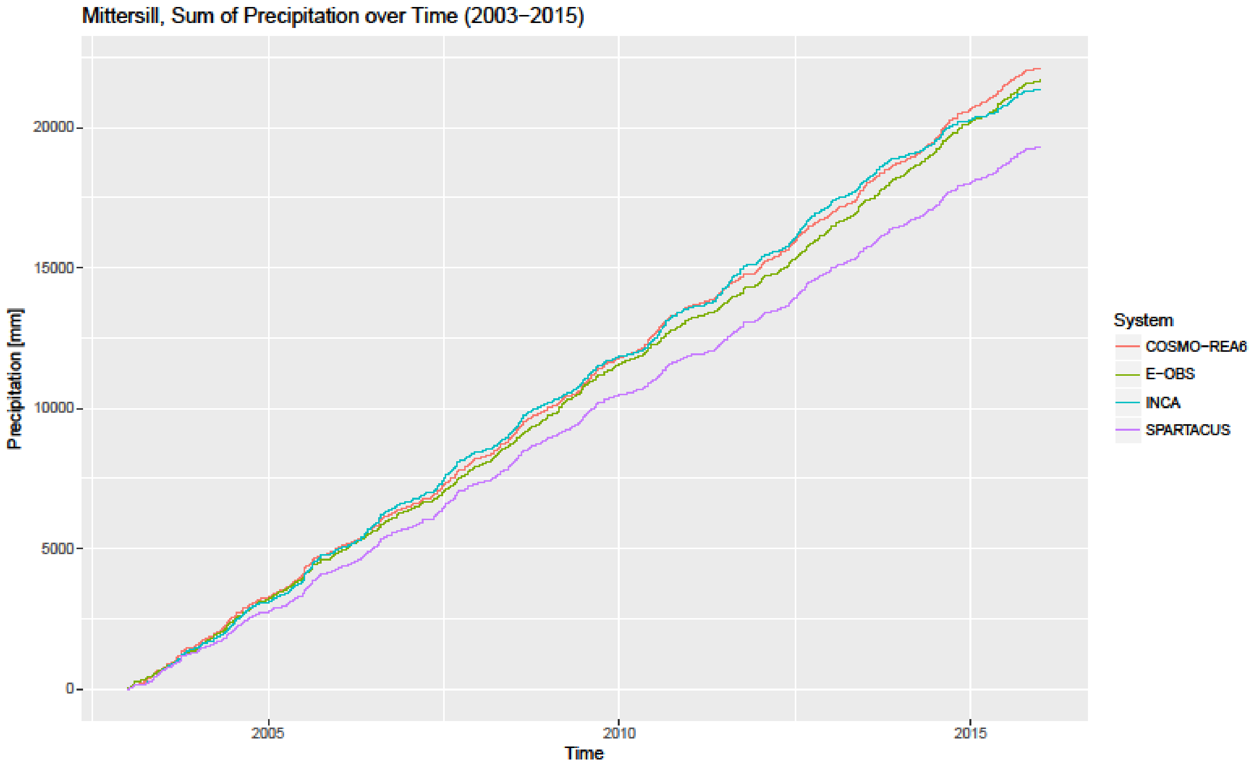

Figure 10-26: Sum of precipitation over time – Mittersill

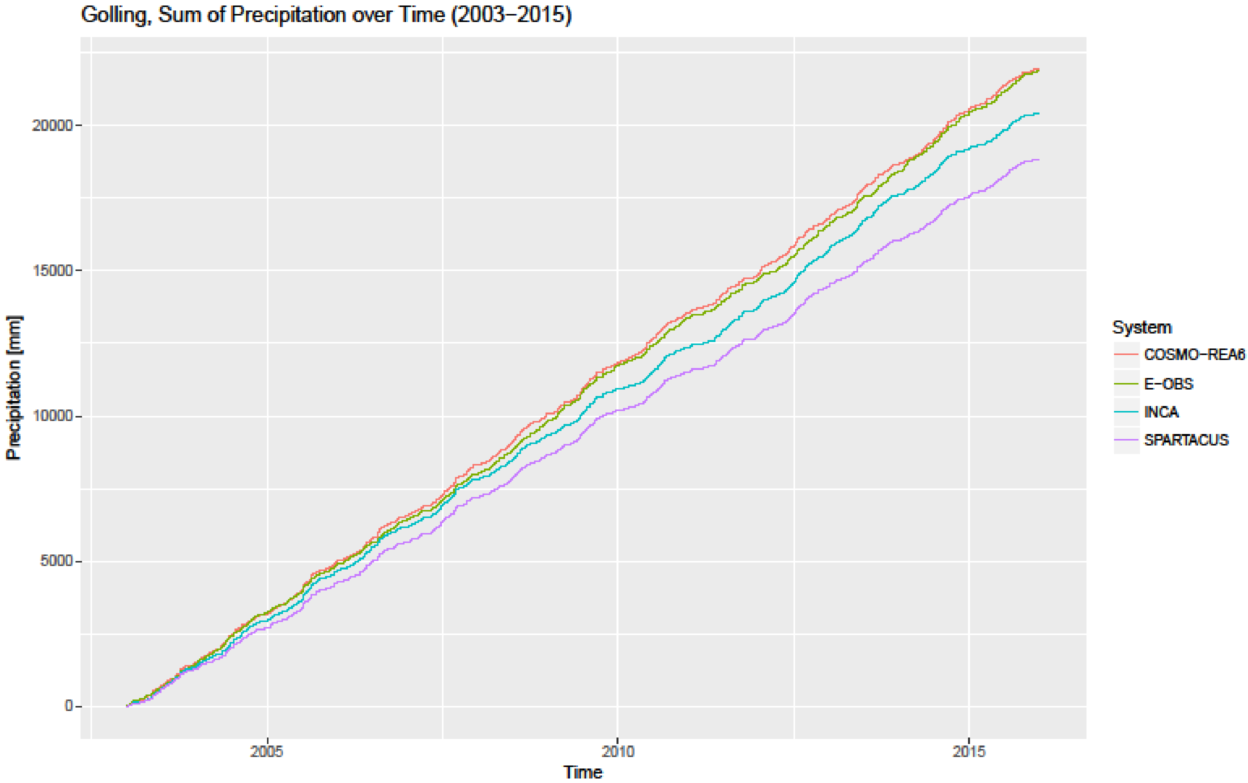

Figure 10-27: Sum of precipitation over time – Golling

10.14 Sum of precipitation over time – Ybbs

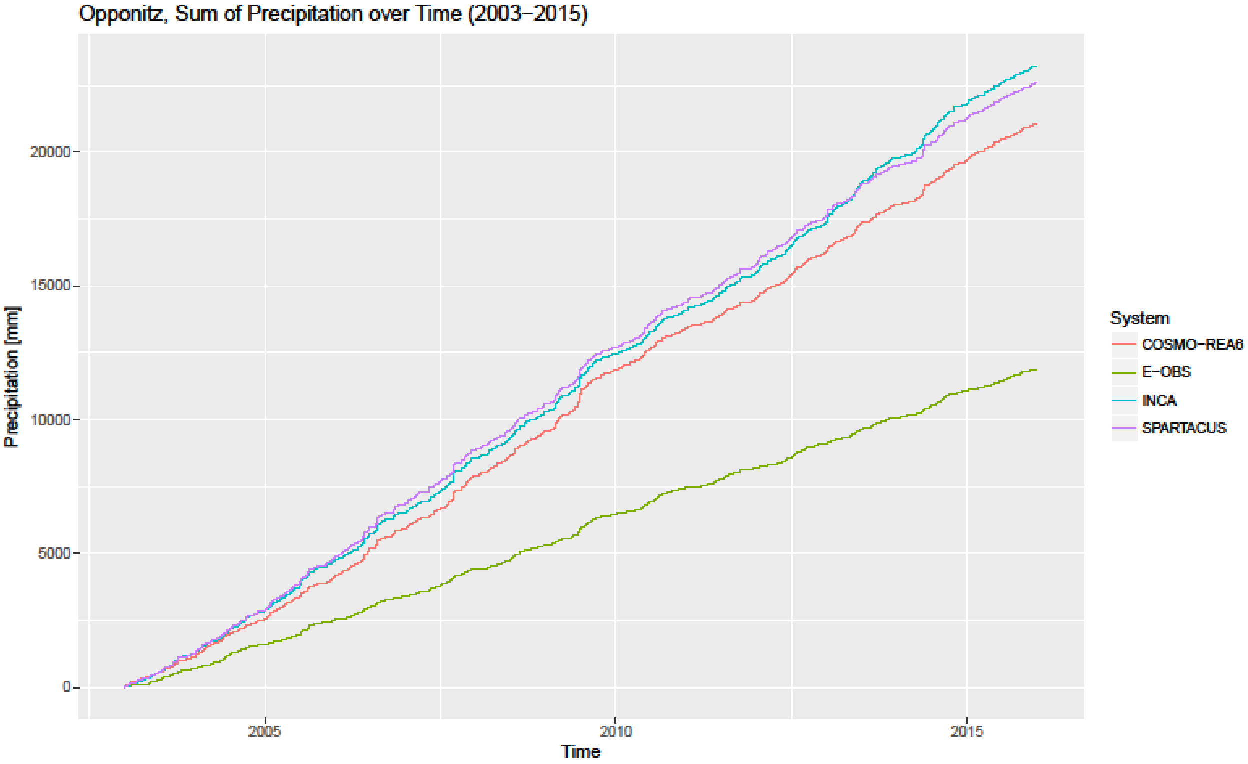

Figure 10-28: Sum of precipitation over time – Opponitz

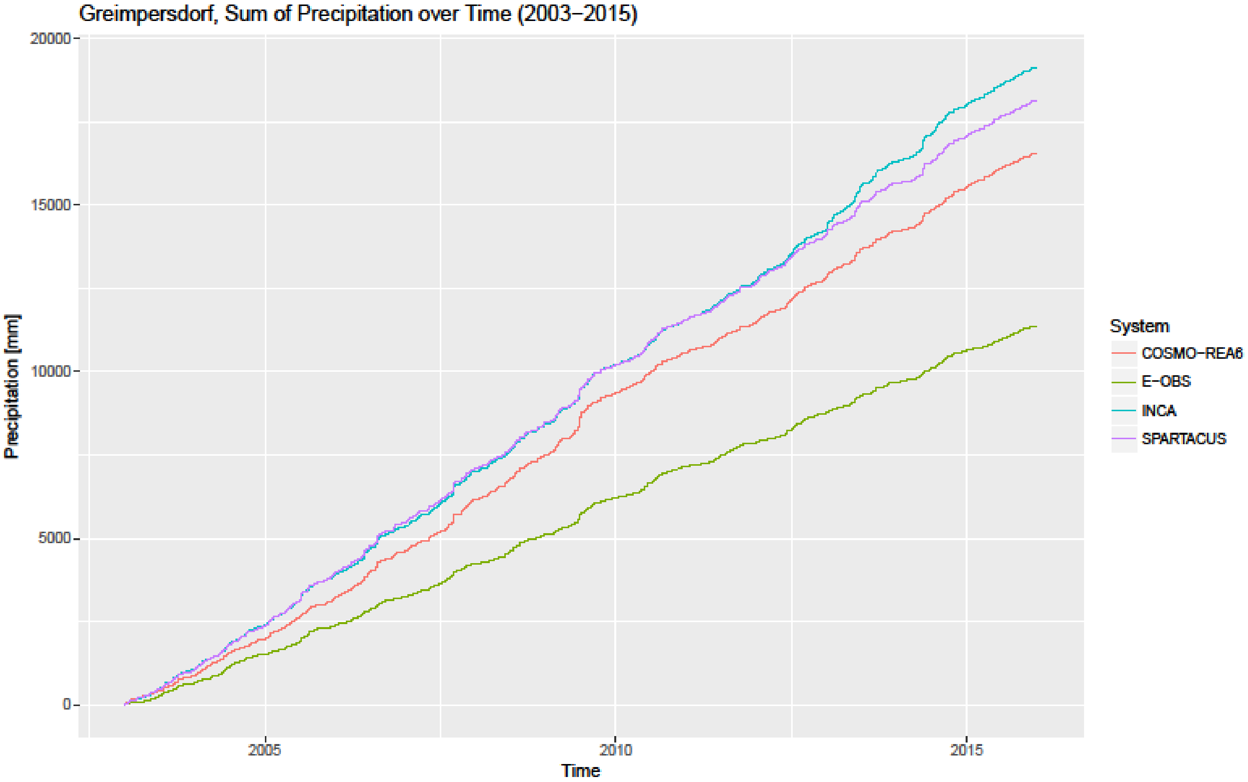

Figure 10-29: Sum of precipitation over time – Greimpersdorf

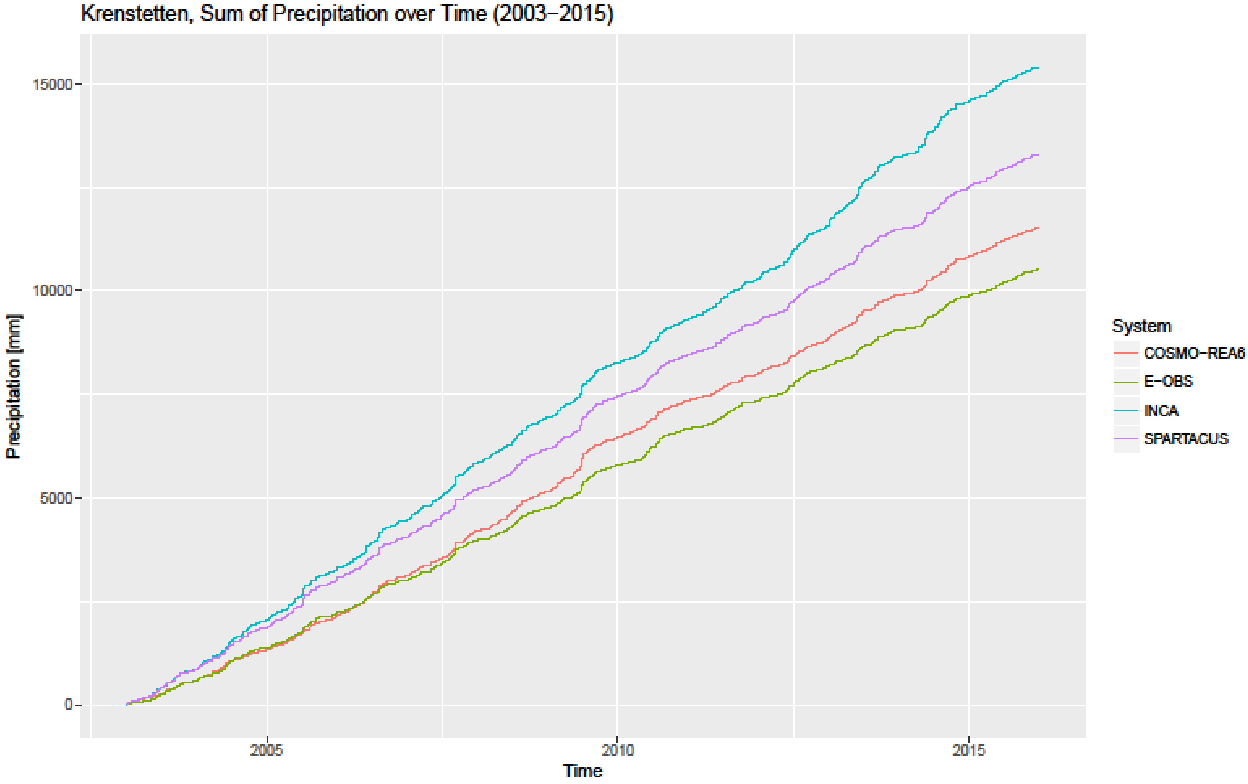

Figure 10-30: Sum of precipitation over time – Krenstetten

10.15 Seasonal residuals of temperature – Salzach

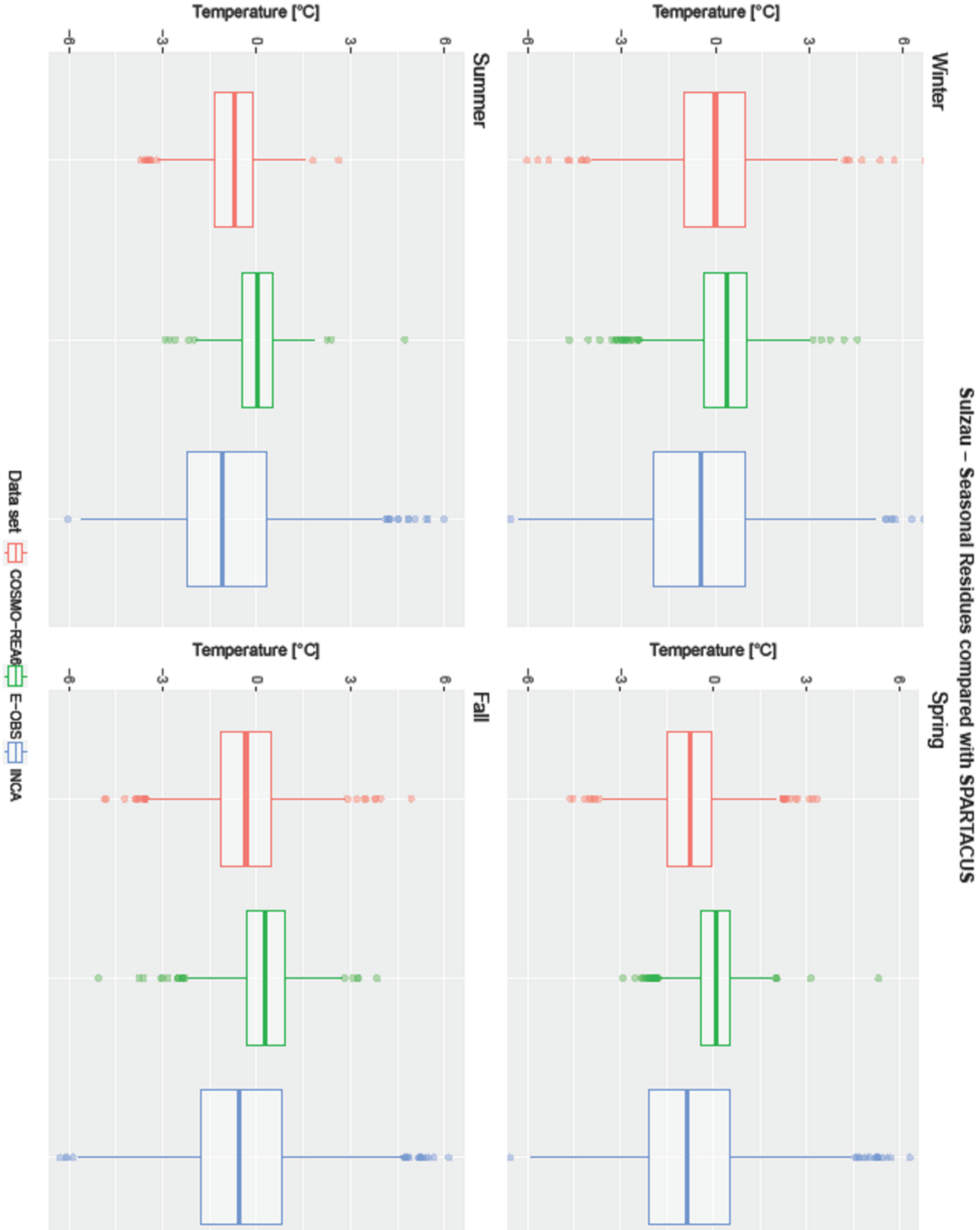

Figure 10-31: Seasonal residuals of temperature – Sulzau

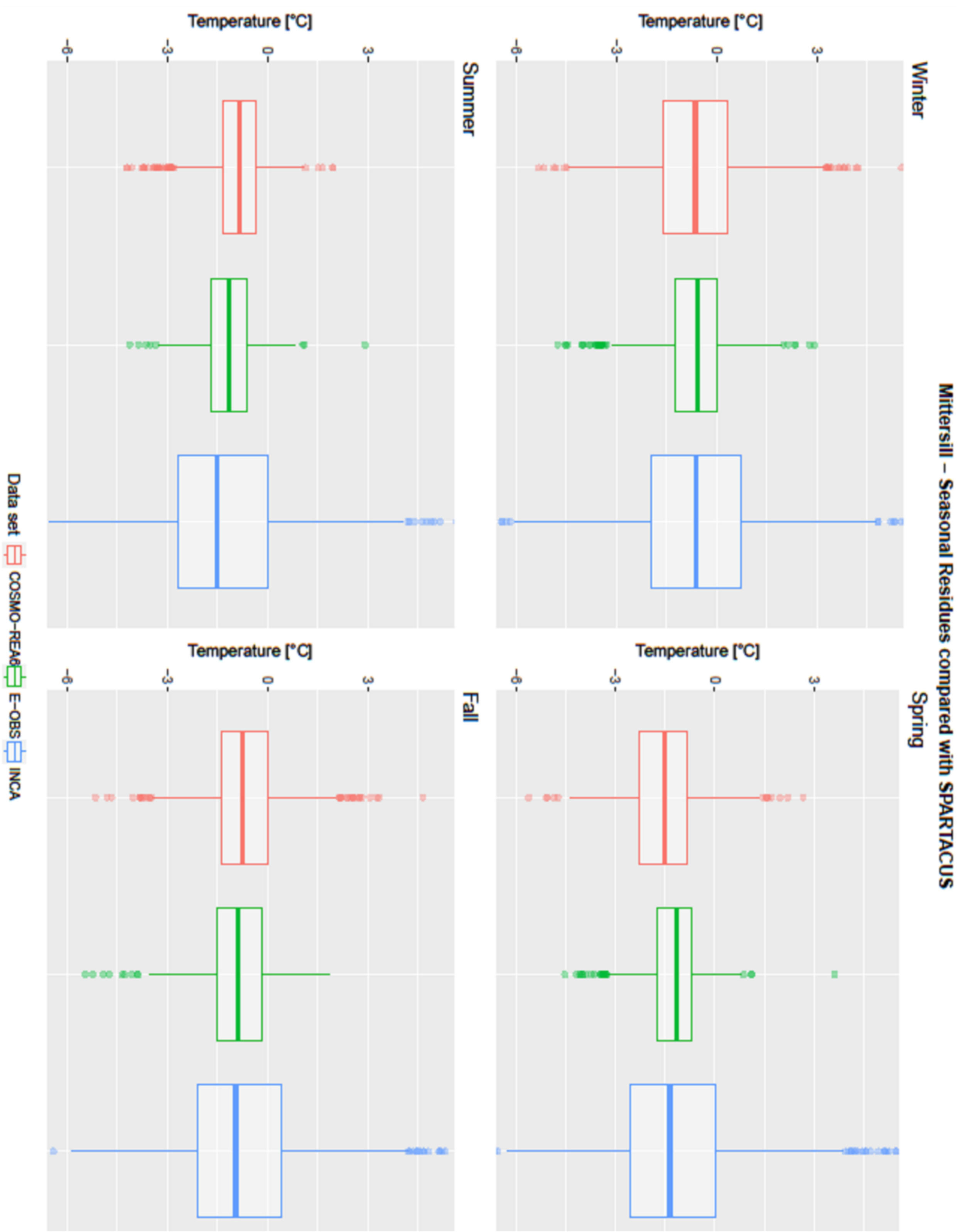

Figure 10-32: Seasonal residuals of temperature – Mittersill

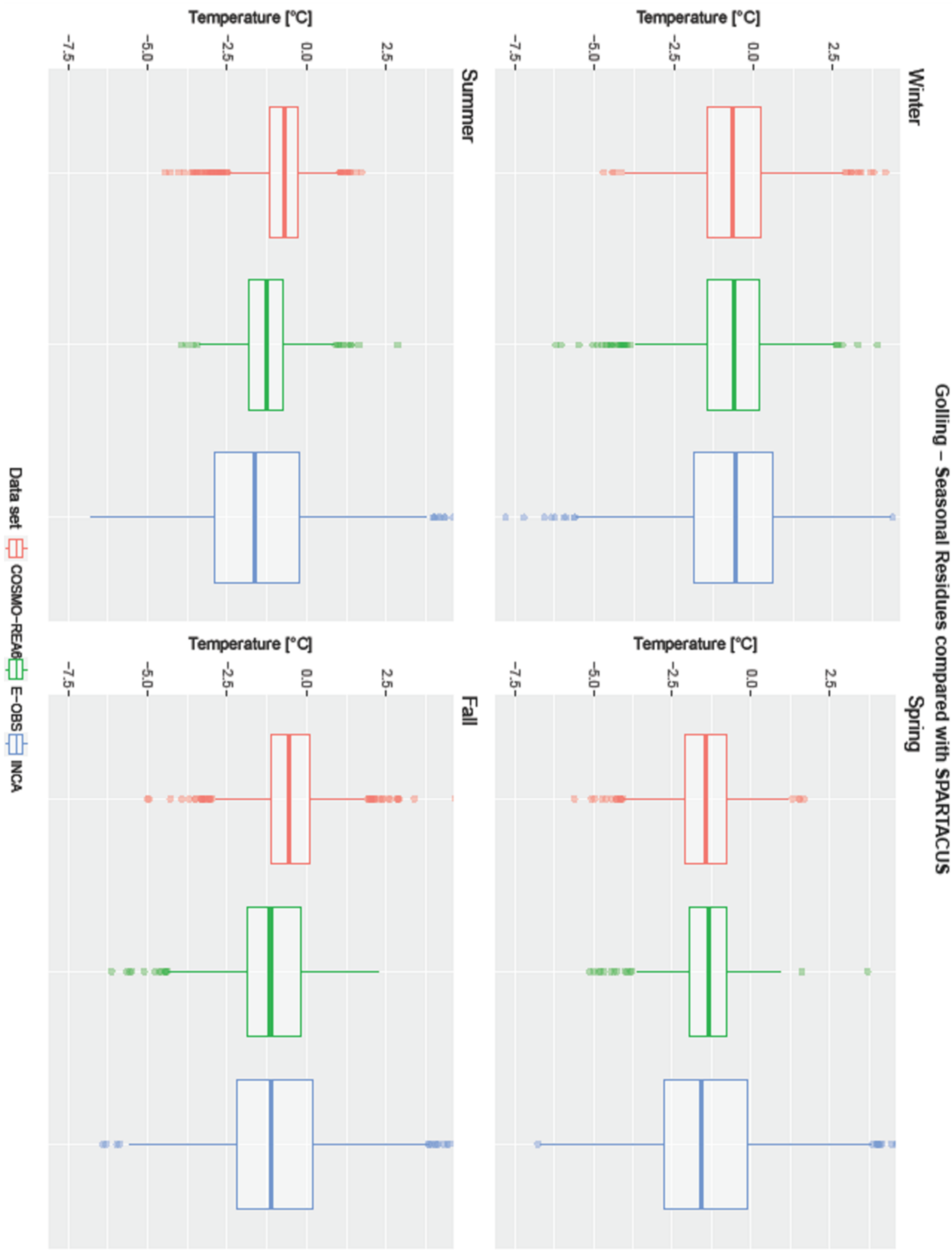

Figure 10-33: Seasonal residuals of temperature – Golling

10.16 Seasonal residuals of temperature – Ybbs

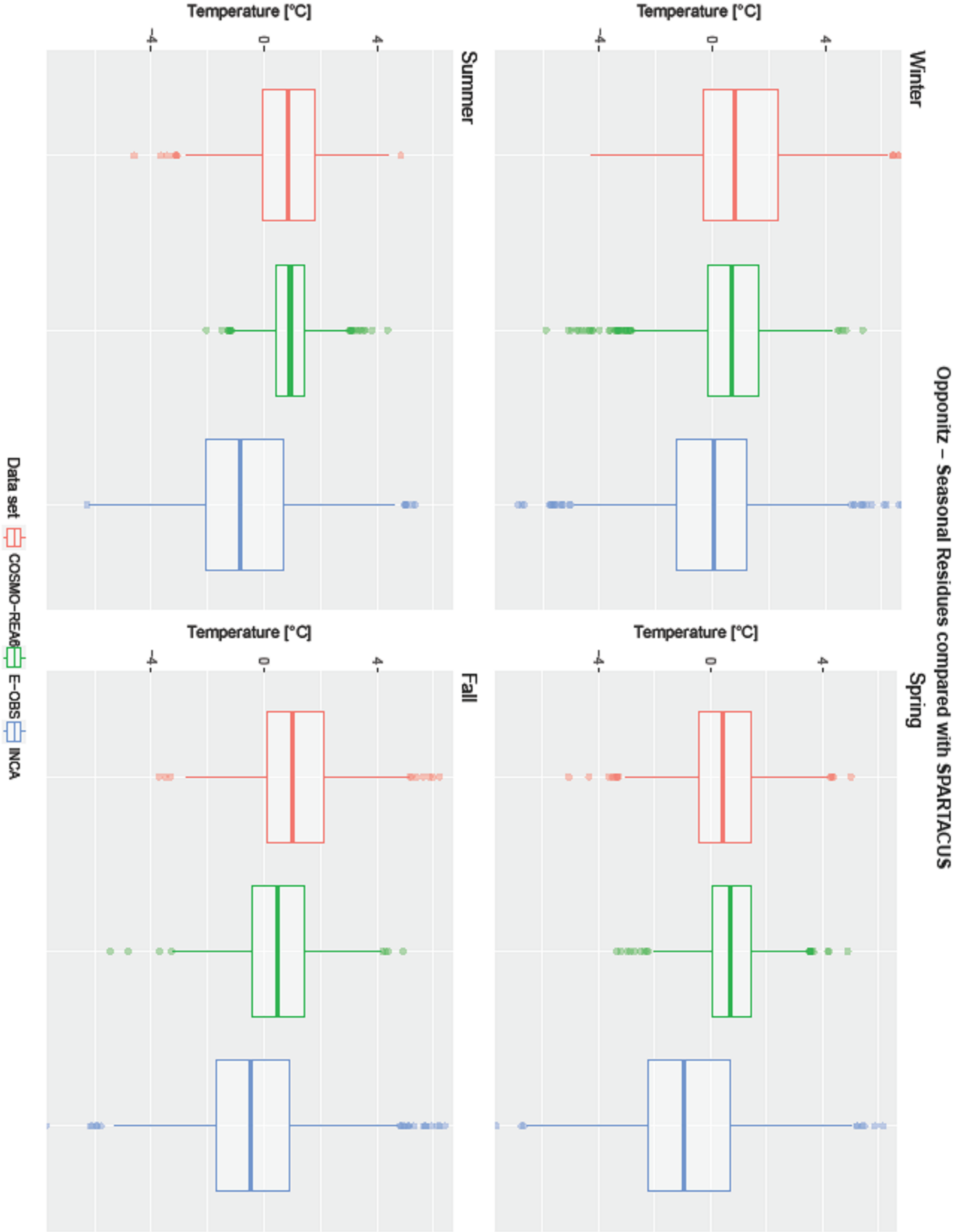

Figure 10-34: Seasonal residuals of temperature – Opponitz

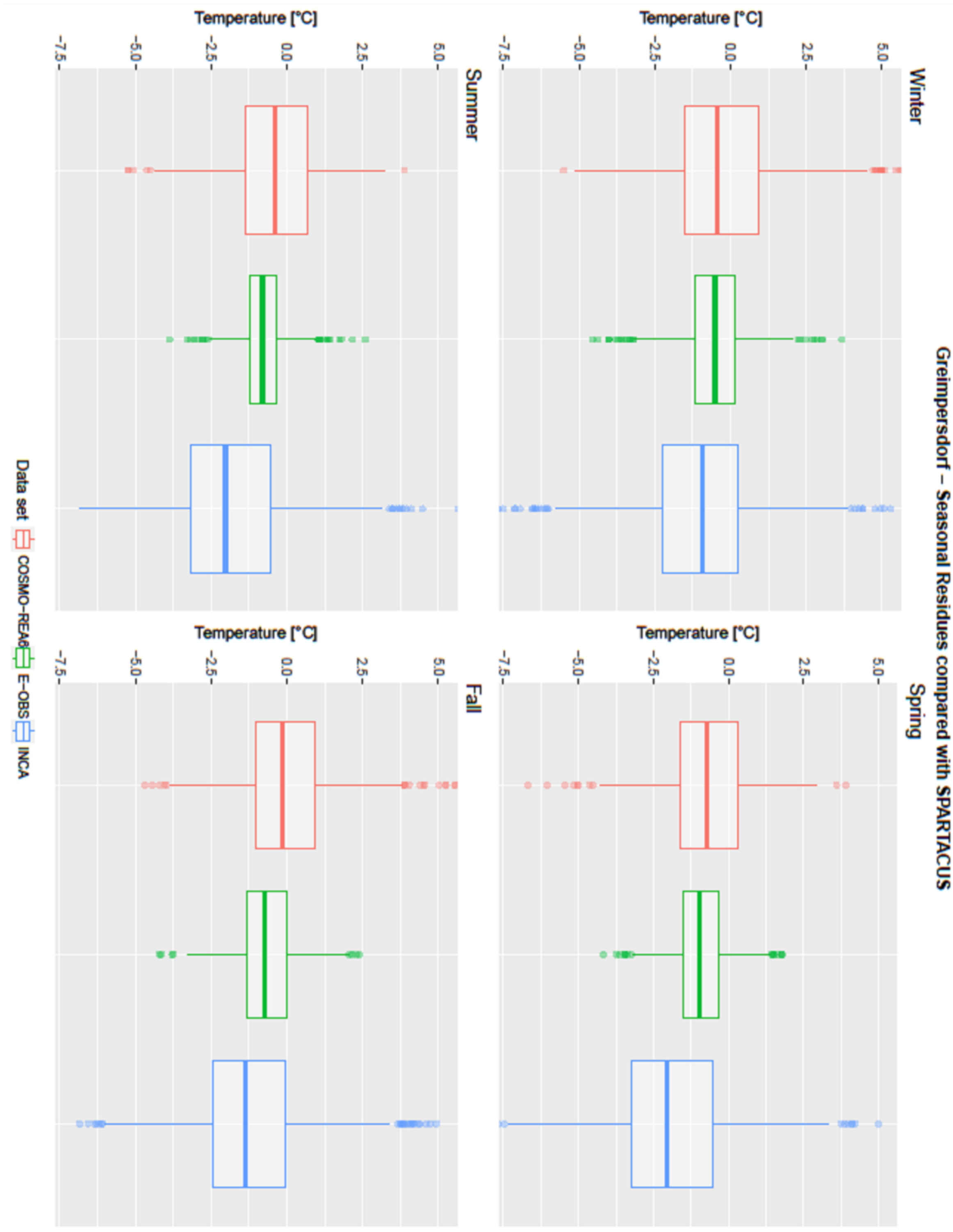

Figure 10-35: Seasonal residuals of temperature – Greimpersdorf

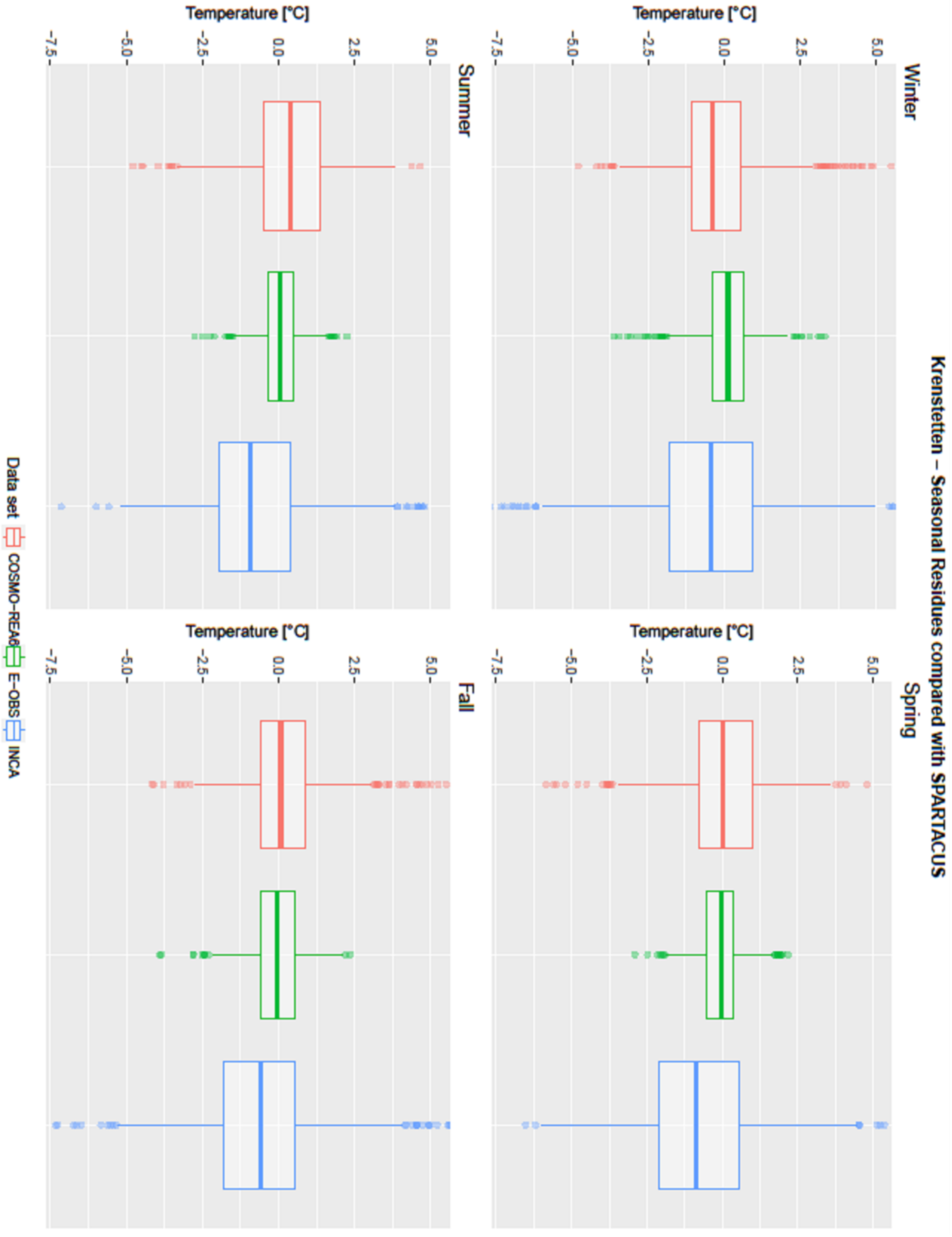

Figure 10-36: Seasonal residuals of temperature – Krenstetten

10.17 Seasonal residuals of precipitation – Salzach

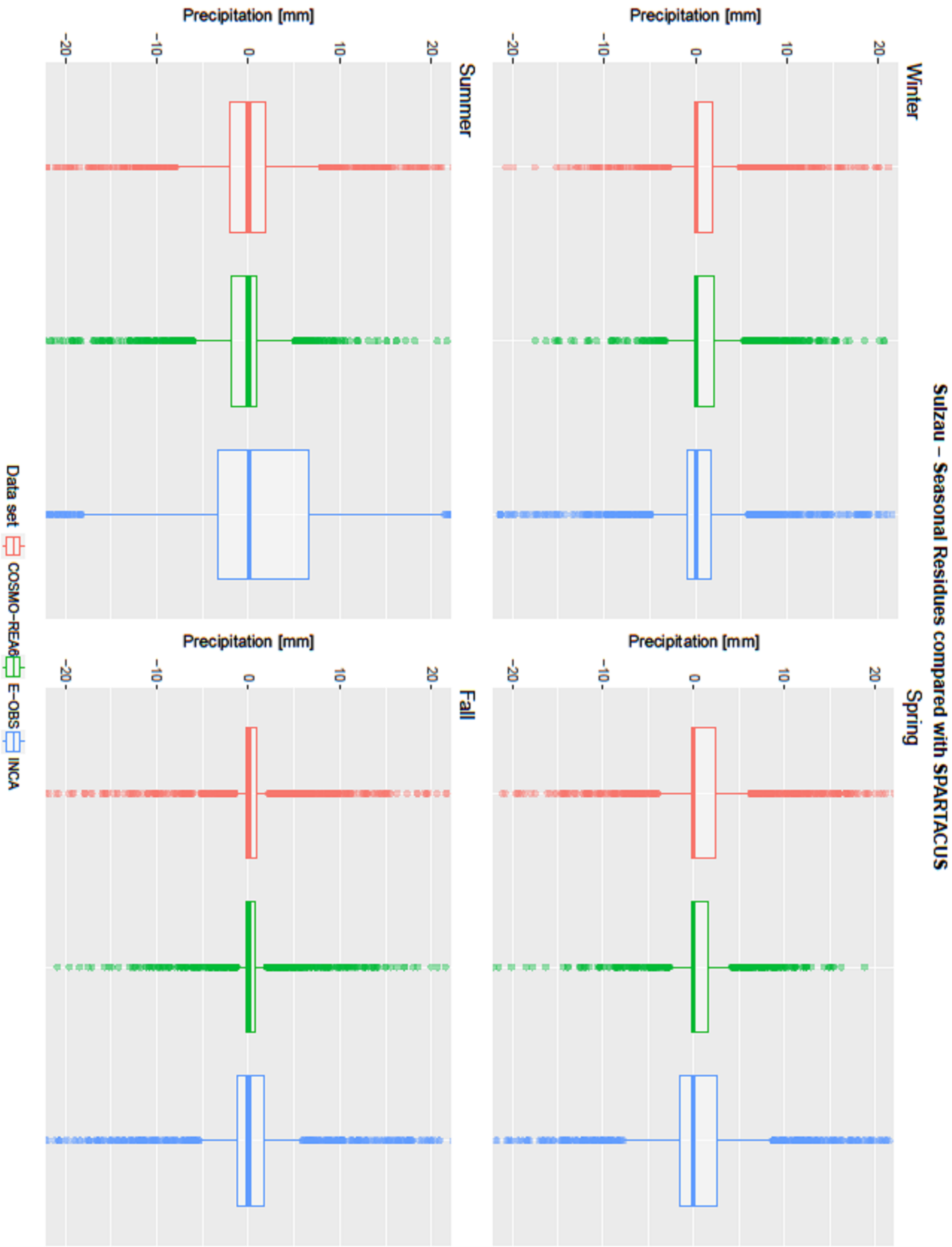

Figure 10-37: Seasonal residuals precipitation – Sulzau

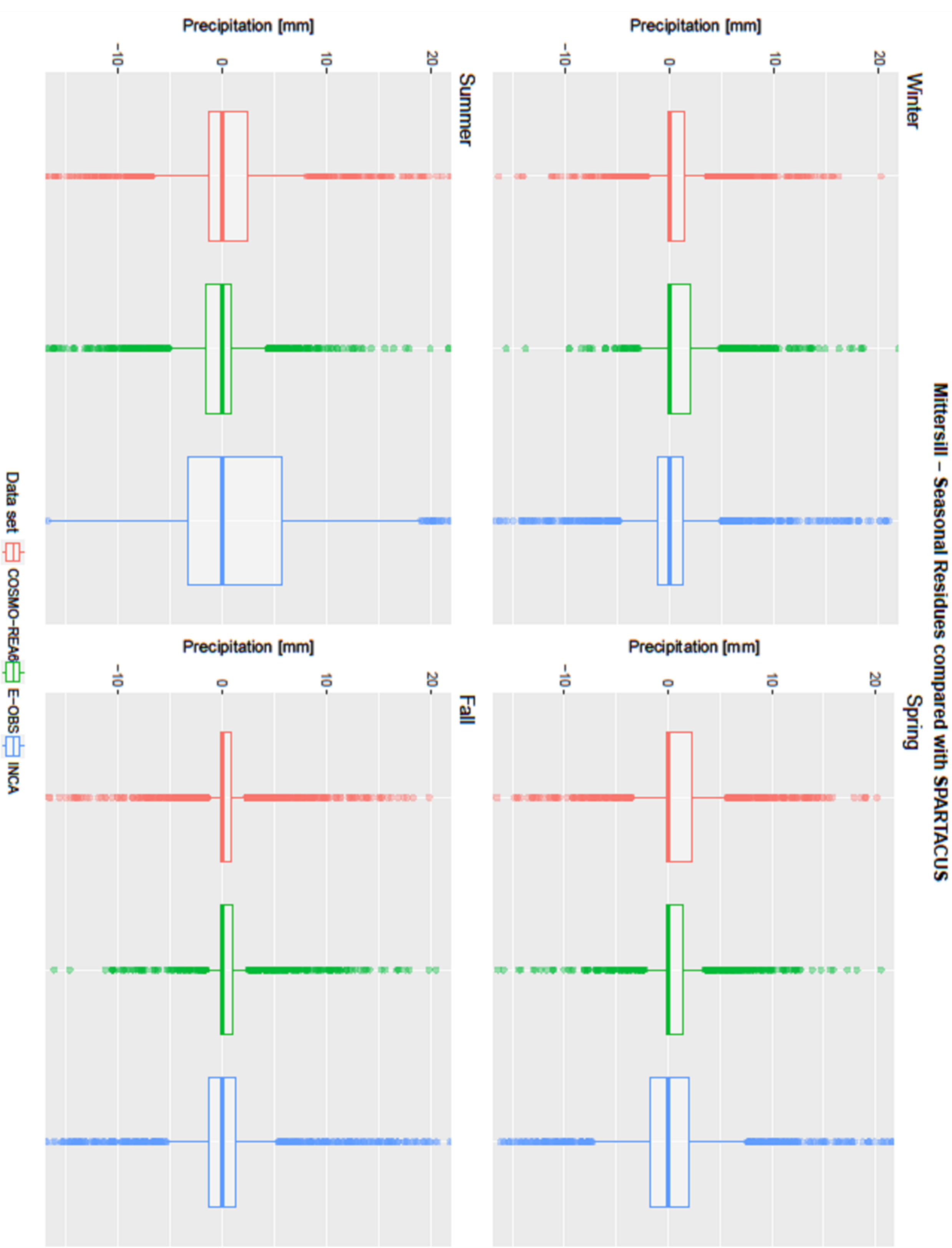

Figure 10-38: Seasonal residuals of precipitation – Mittersill

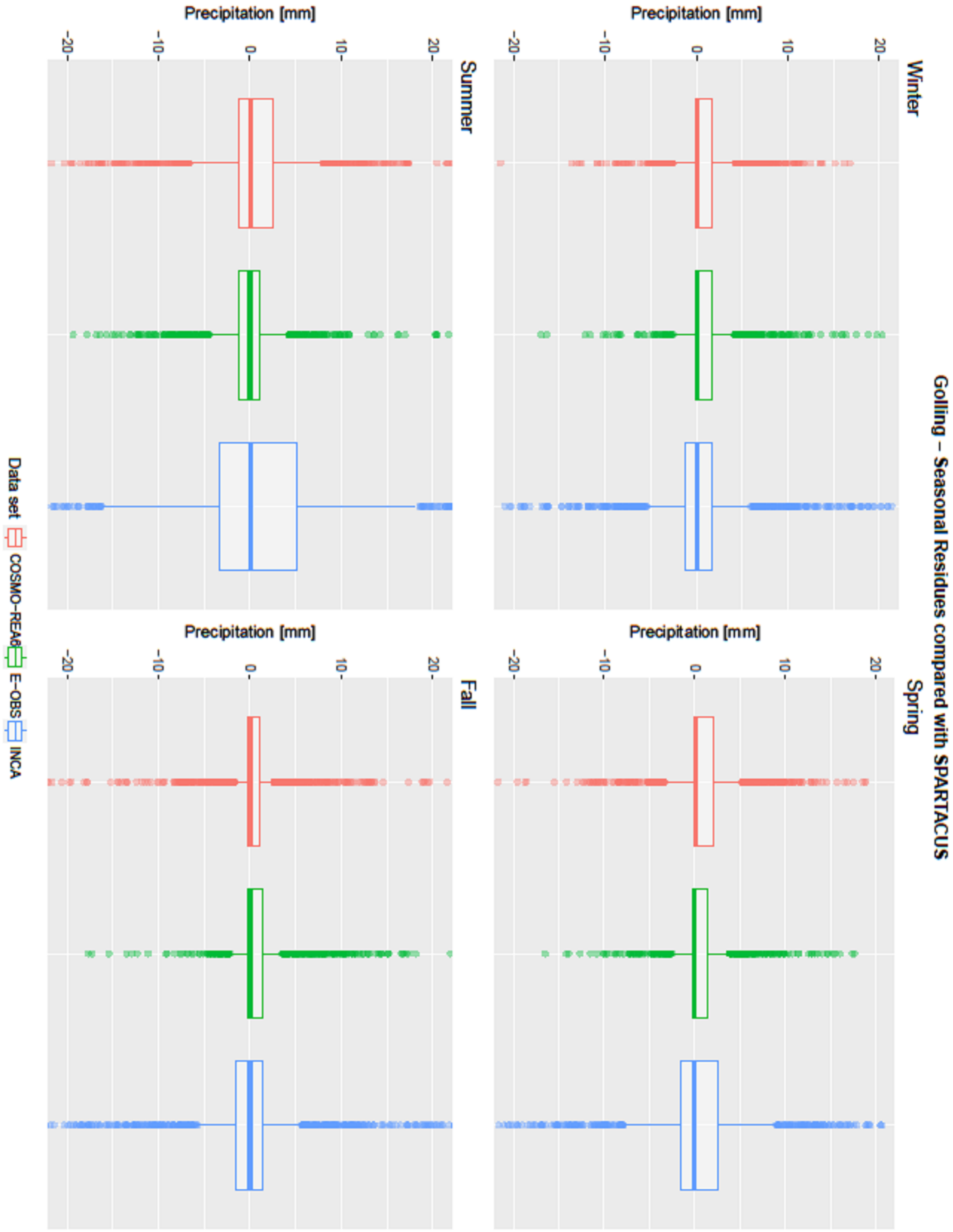

Figure 10-39: Seasonal residuals of precipitation – Golling

10.18 Seasonal residuals of precipitation – Ybbs

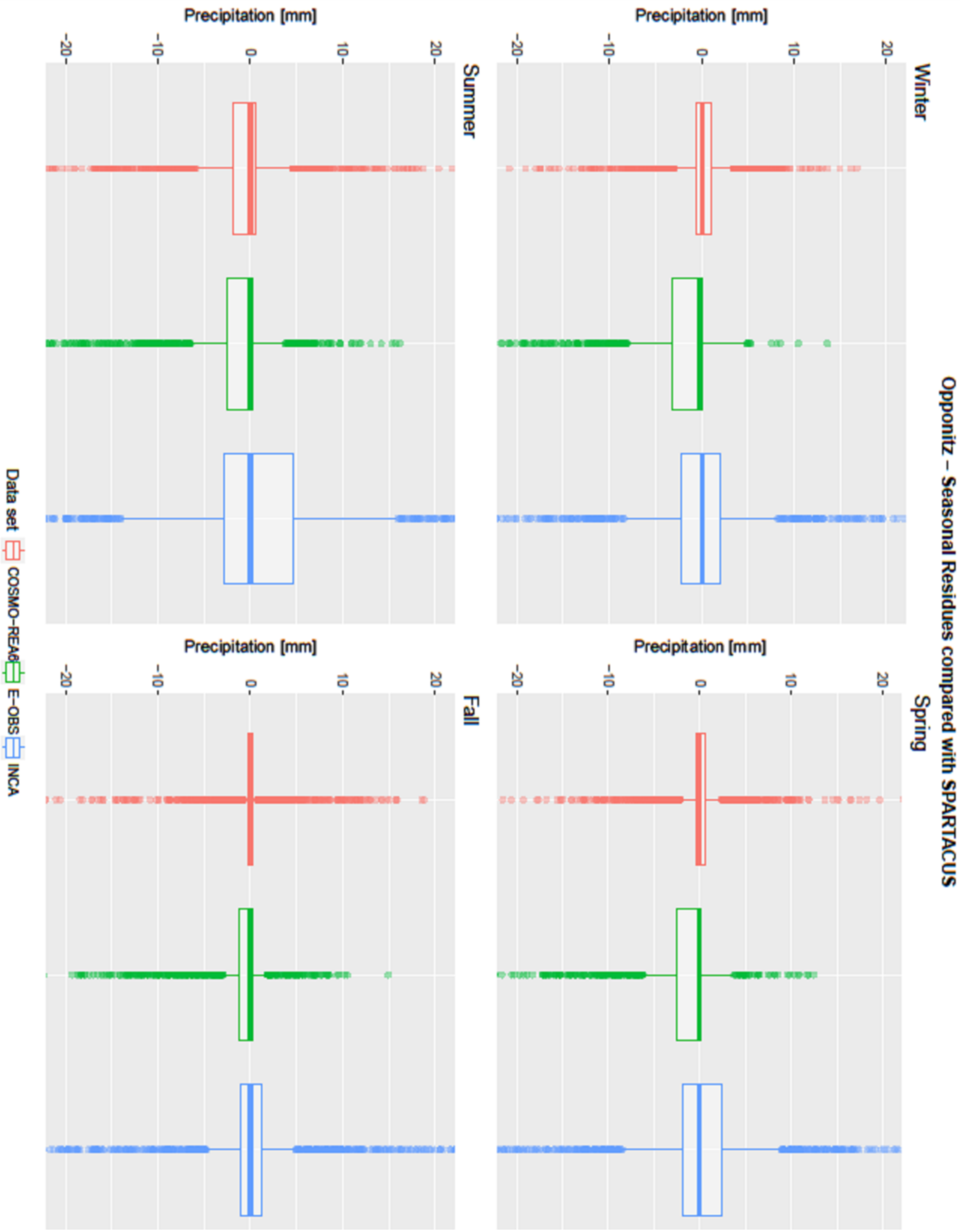

Figure 10-40: Seasonal residuals of precipitation – Opponitz

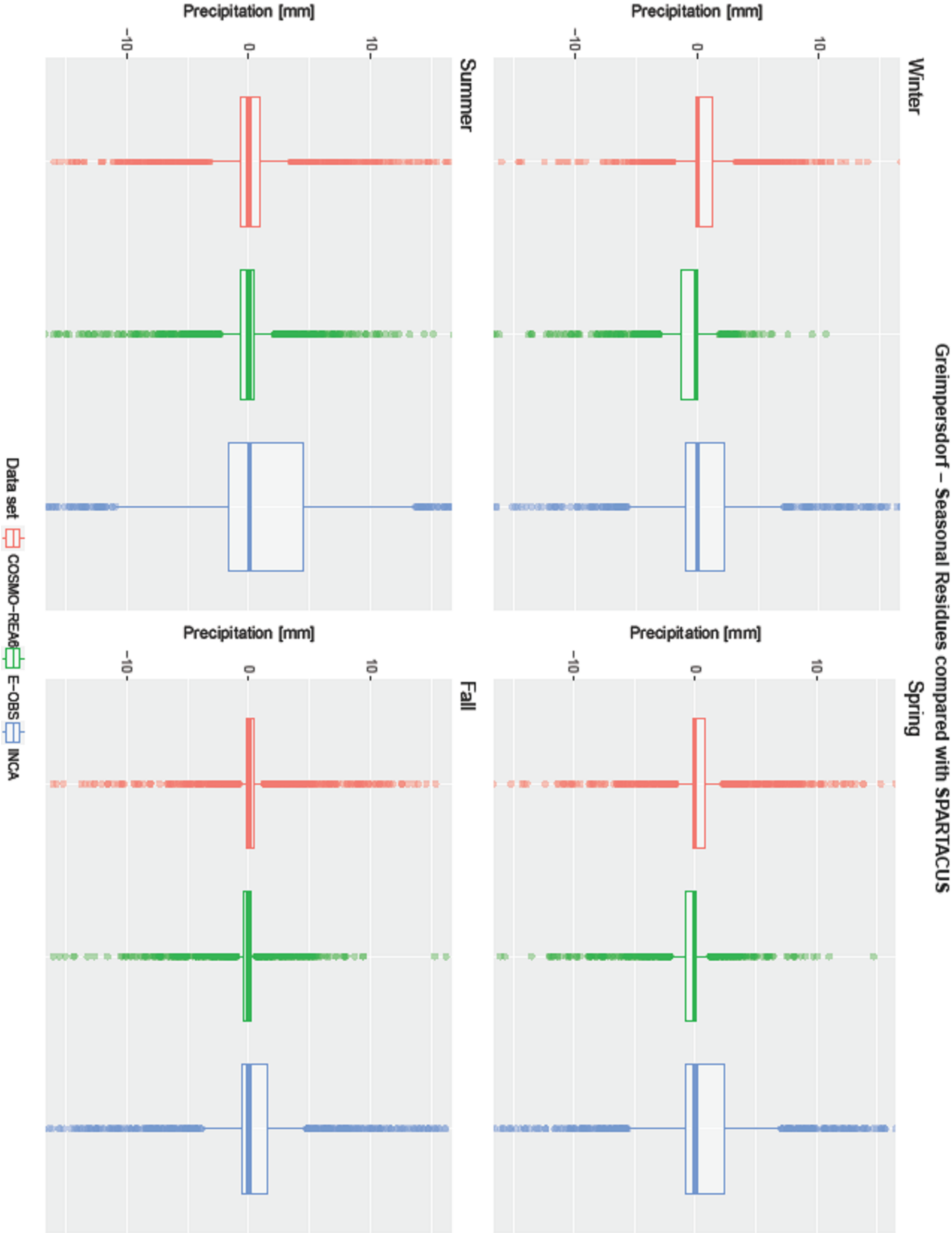

Figure 10-41: Seasonal residuals of precipitation – Greimpersdorf

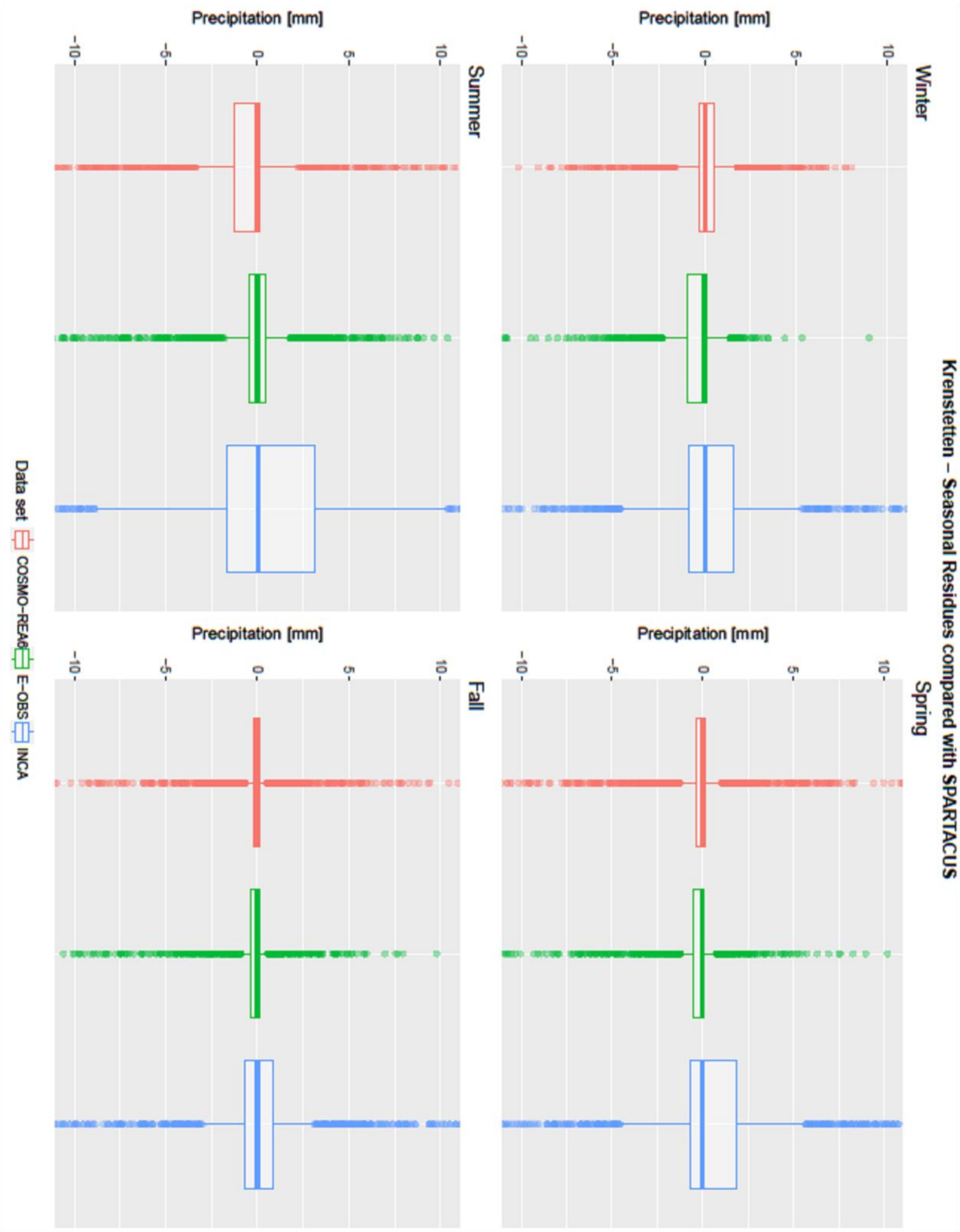

Figure 10-42: Seasonal residuals of precipitation – Krenstetten

10.19 Maps of mean daily temperature in Austria

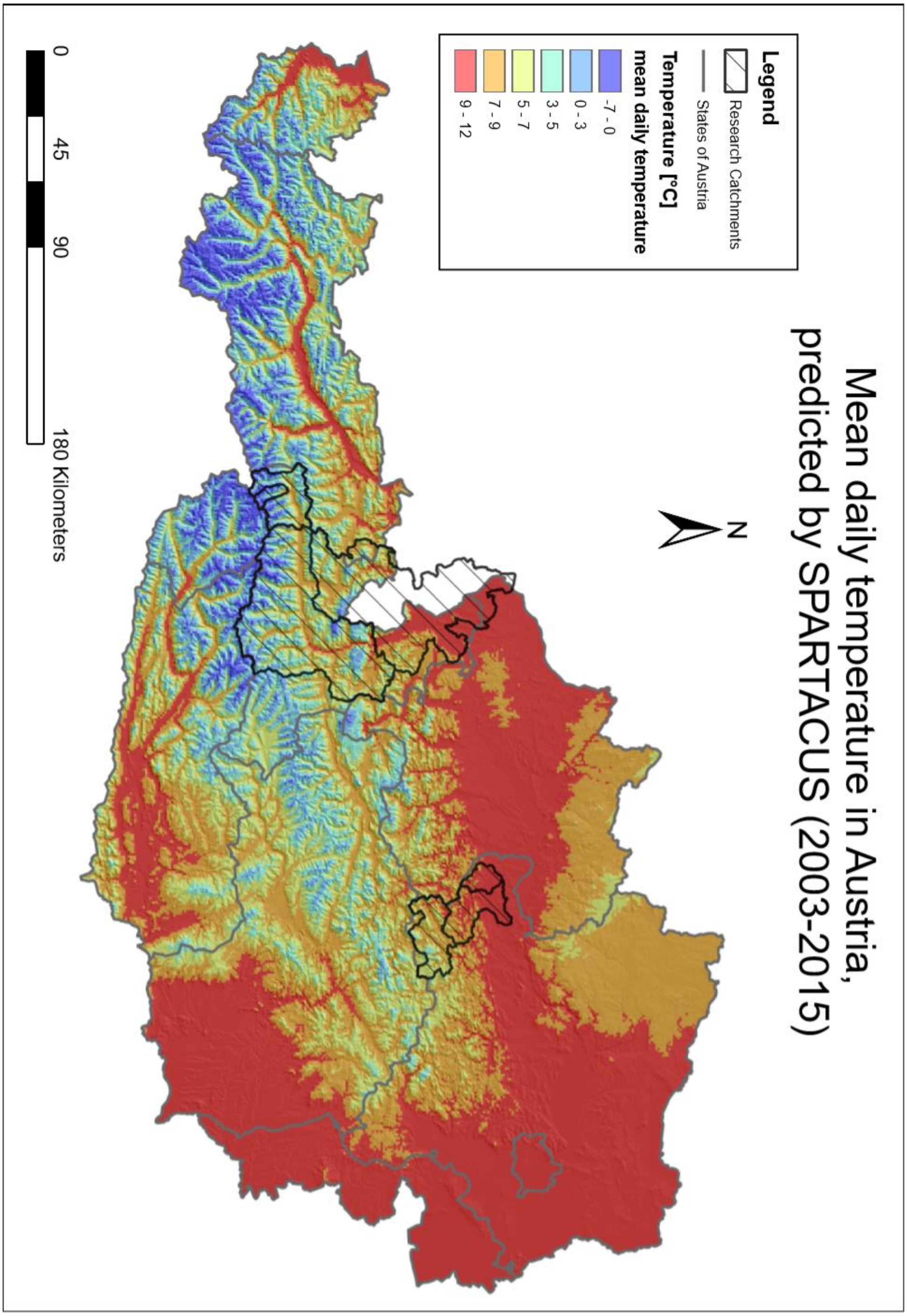

Figure 10-43: Mean daily temperature in Austria, predicted by SPARTACUS

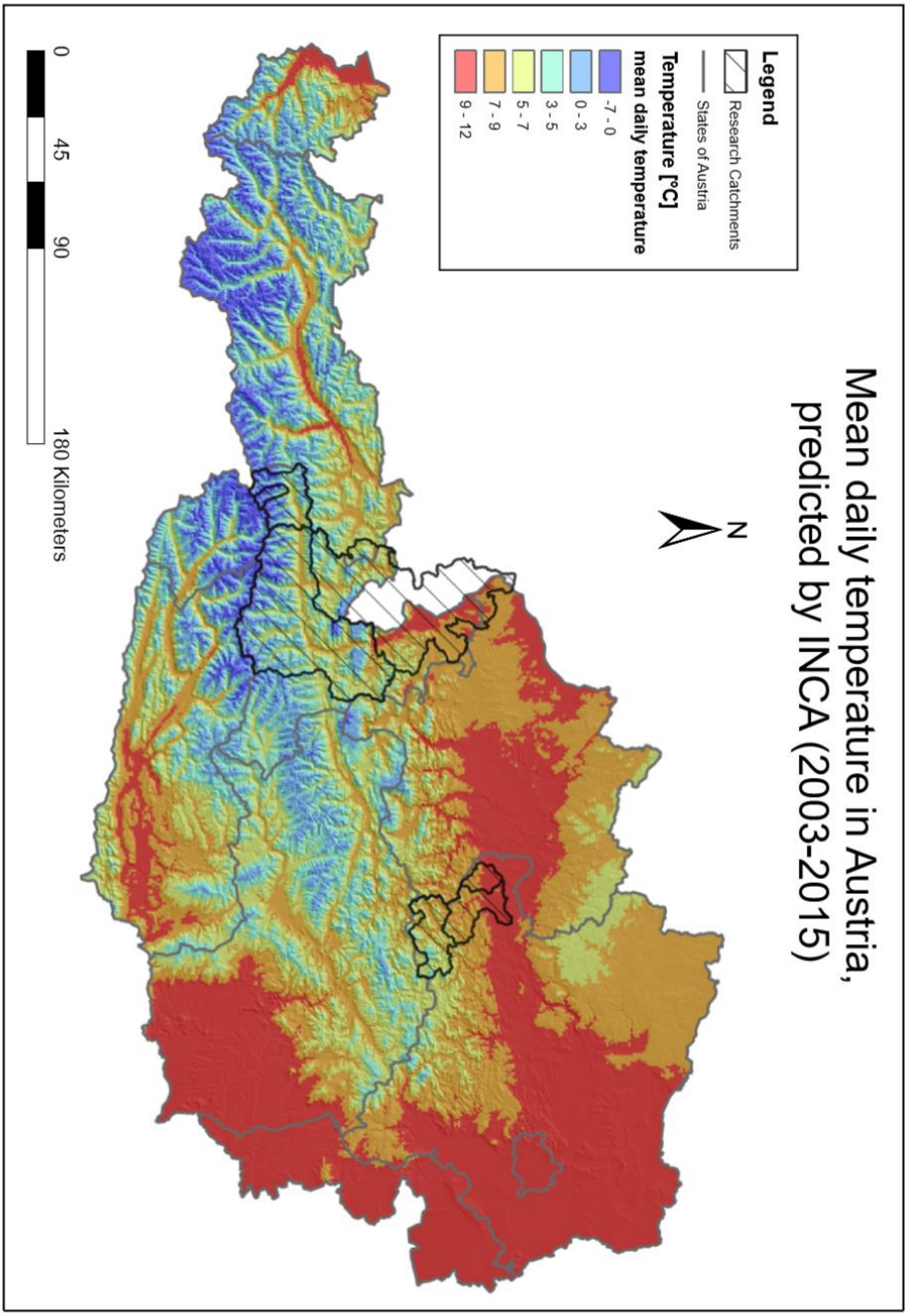

Figure 10-44: Mean daily temperature in Austria, predicted by INCA

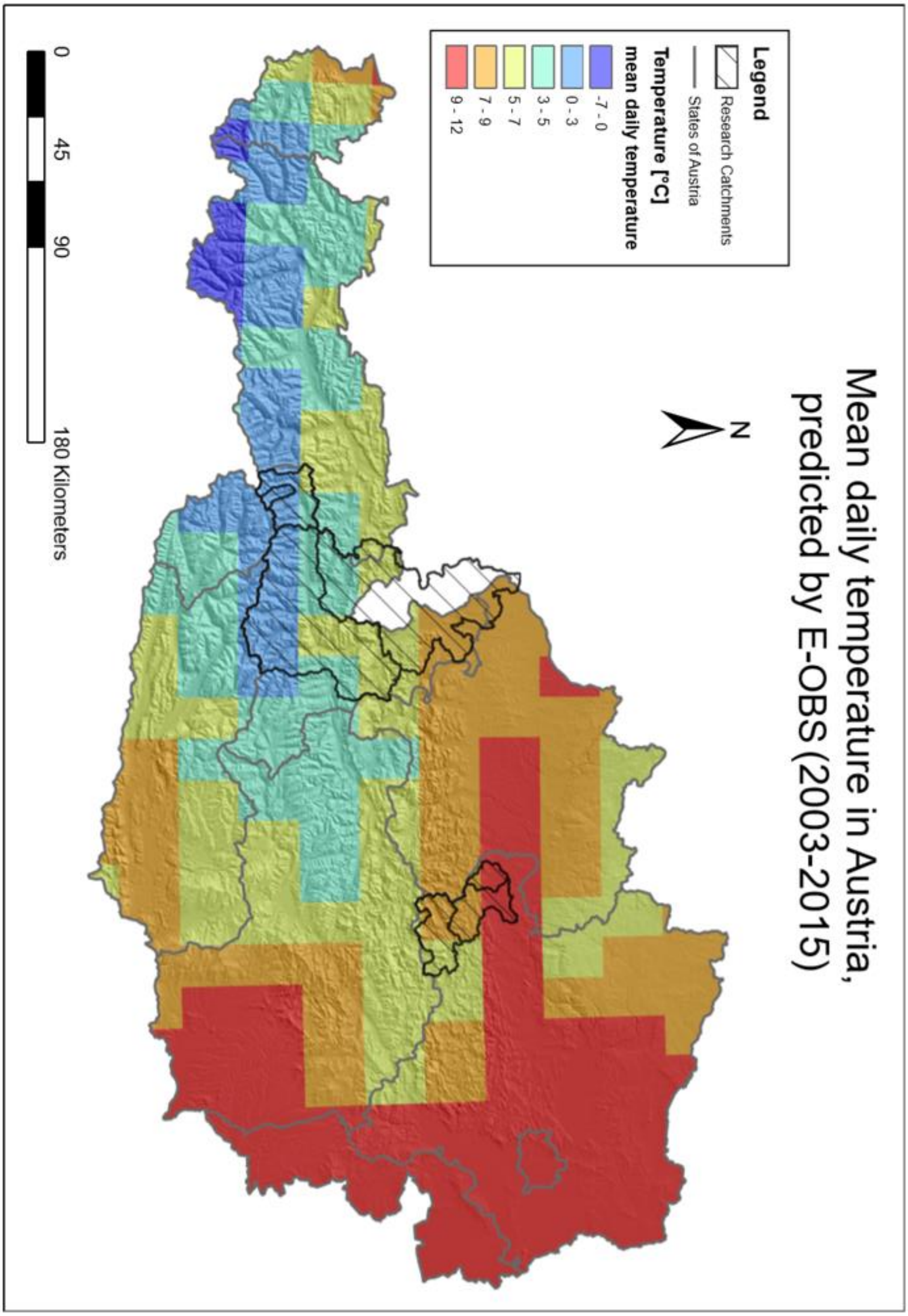

Figure 10-45: Mean daily temperature in Austria, predicted by E-OBS

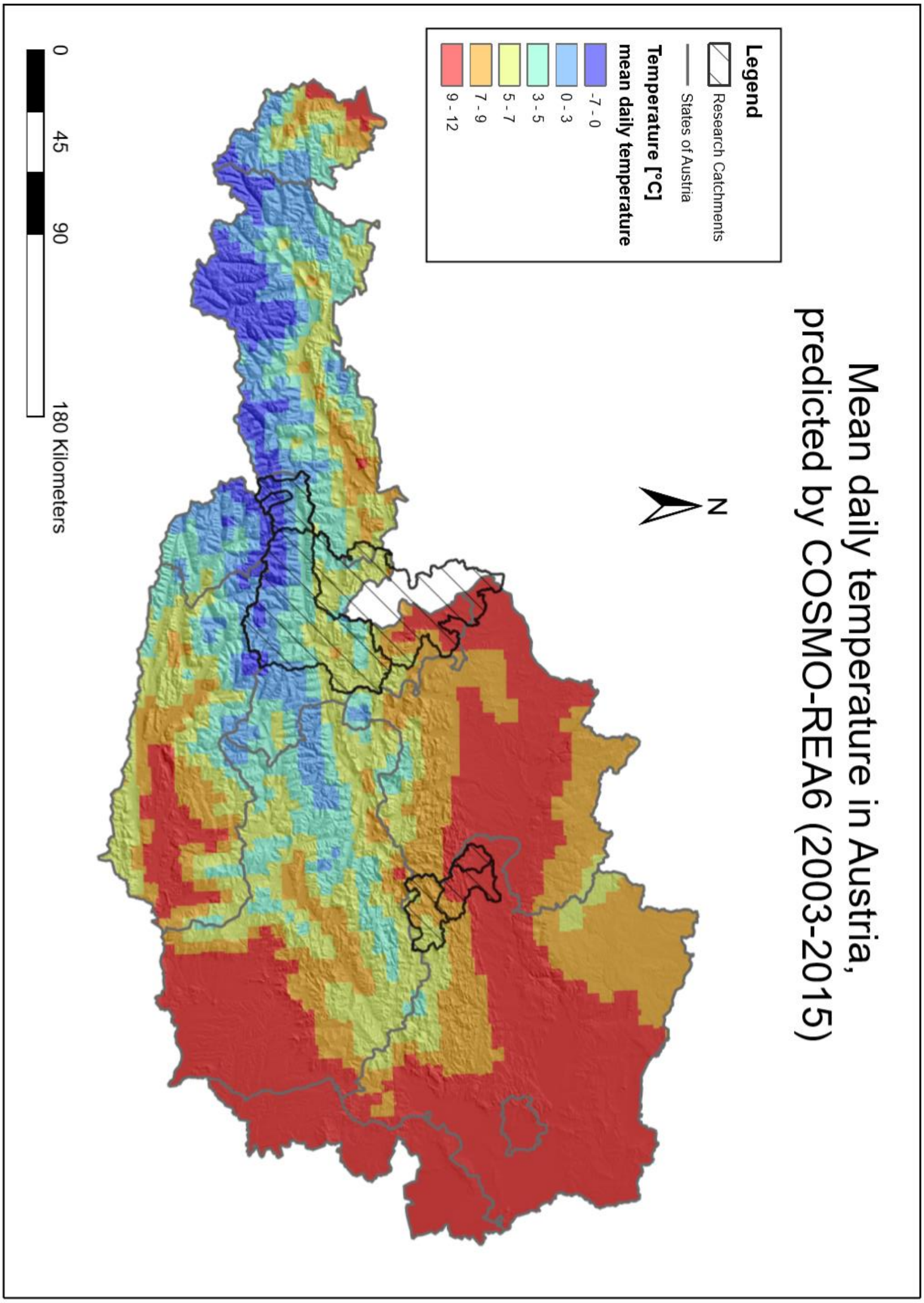

Figure 10-46: Mean daily temperature in Austria, predicted by COSMO-REA6

10.20 Maps of mean annual precipitation sum in Austria

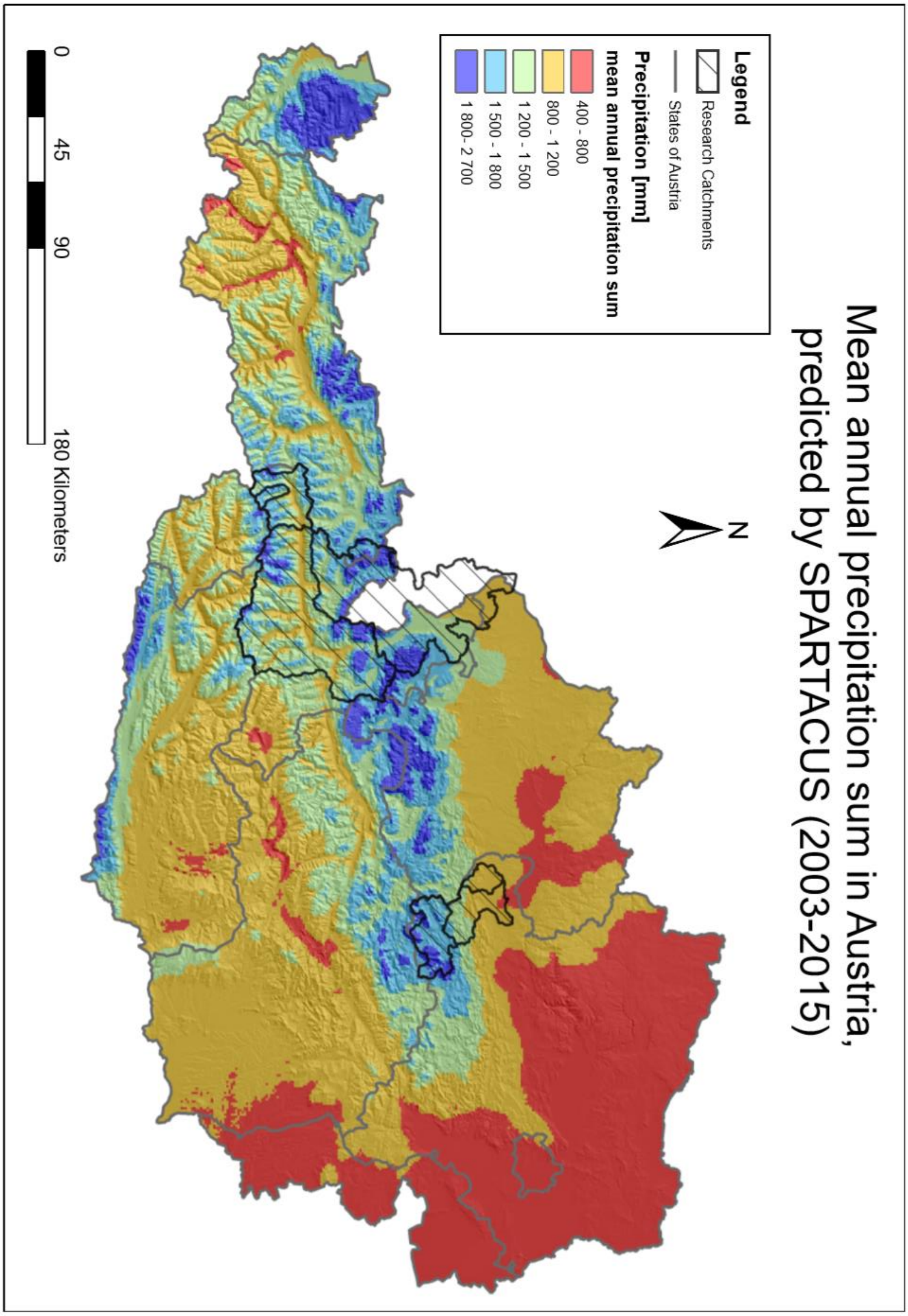

Figure 10-47: Mean annual precipitation sum in Austria, predicted by SPARTACUS

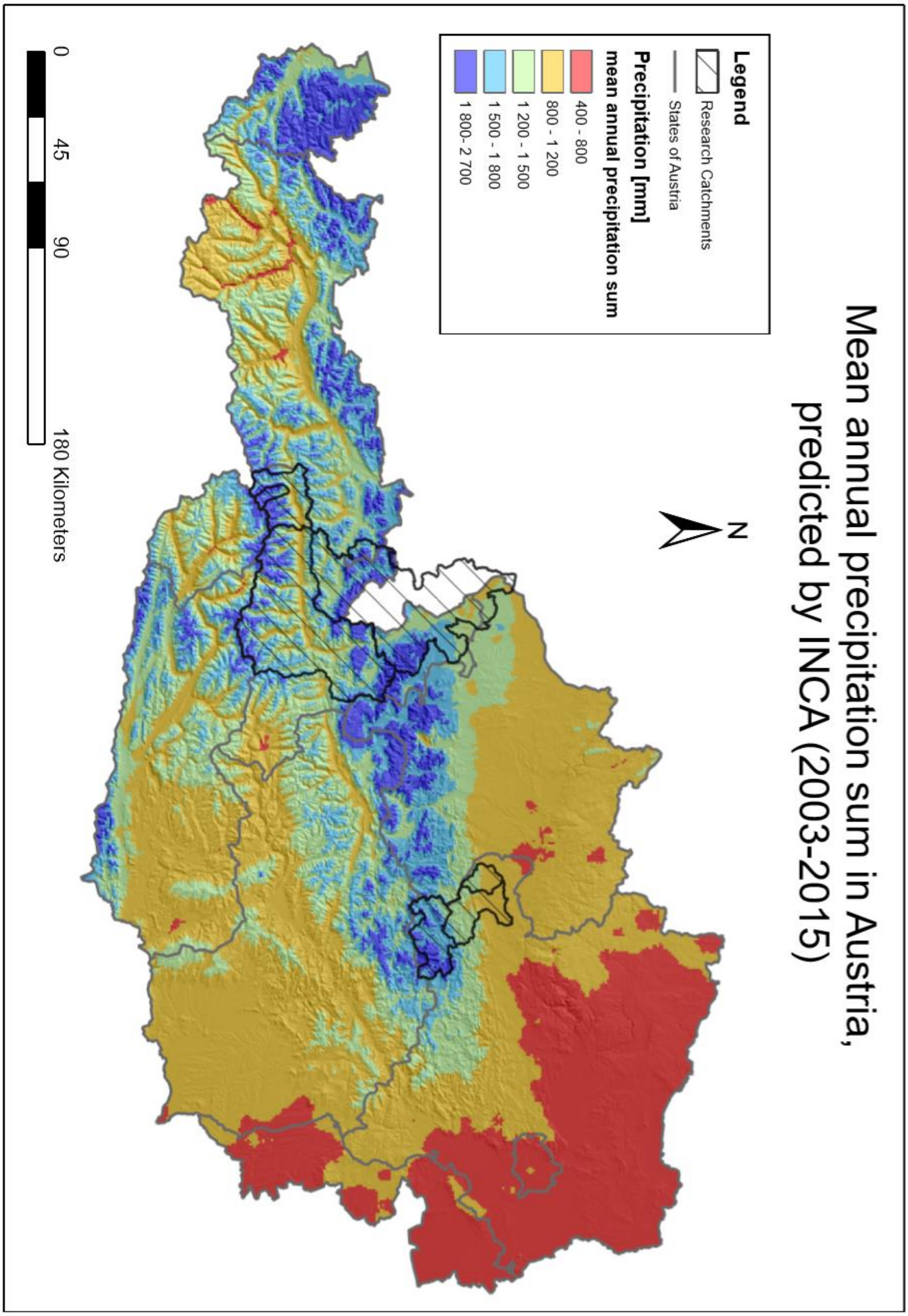

Figure 10-48: Mean annual precipitation sum in Austria, predicted by INCA

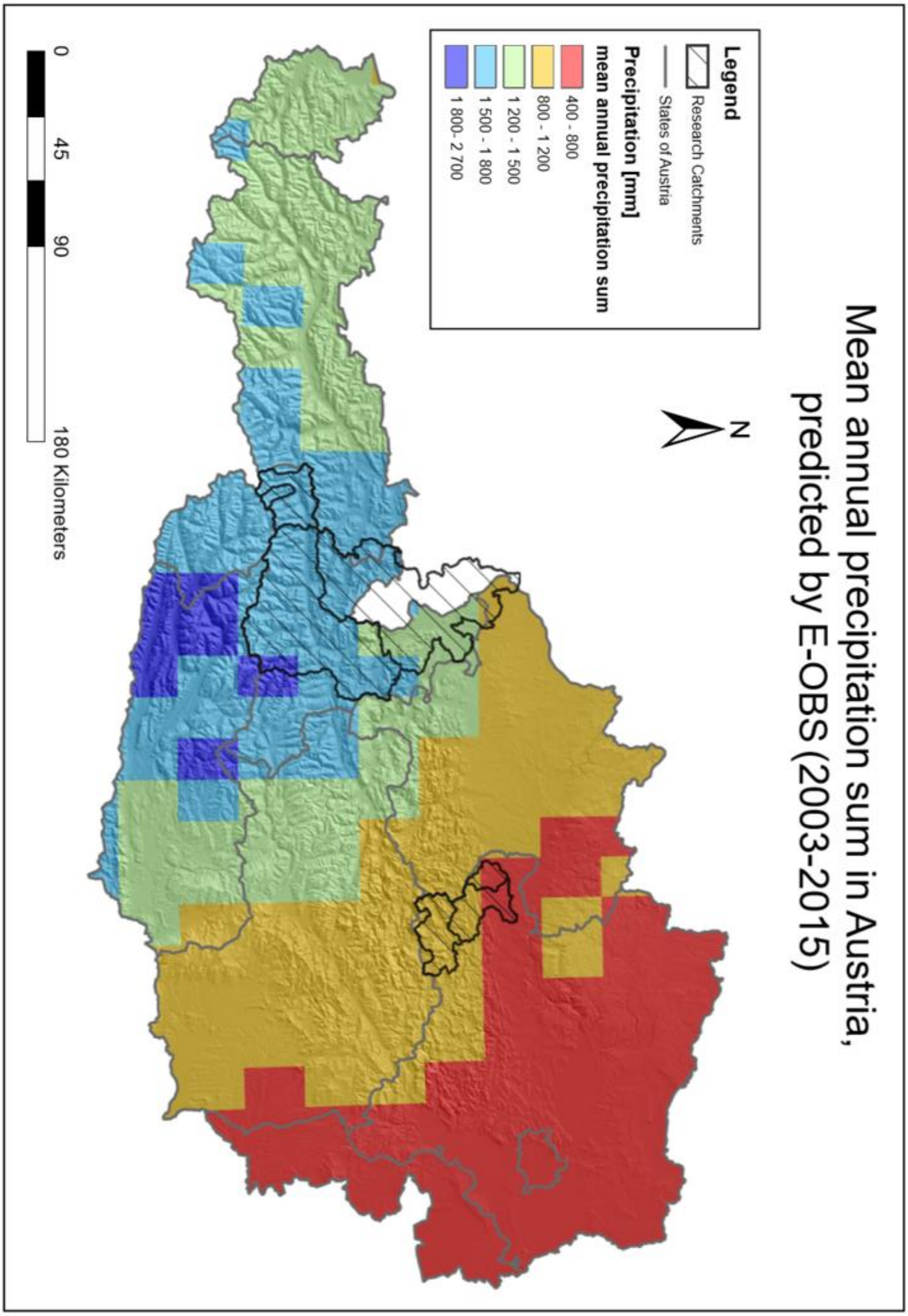

Figure 10-49: Mean annual precipitation sum in Austria, predicted by E-OBS

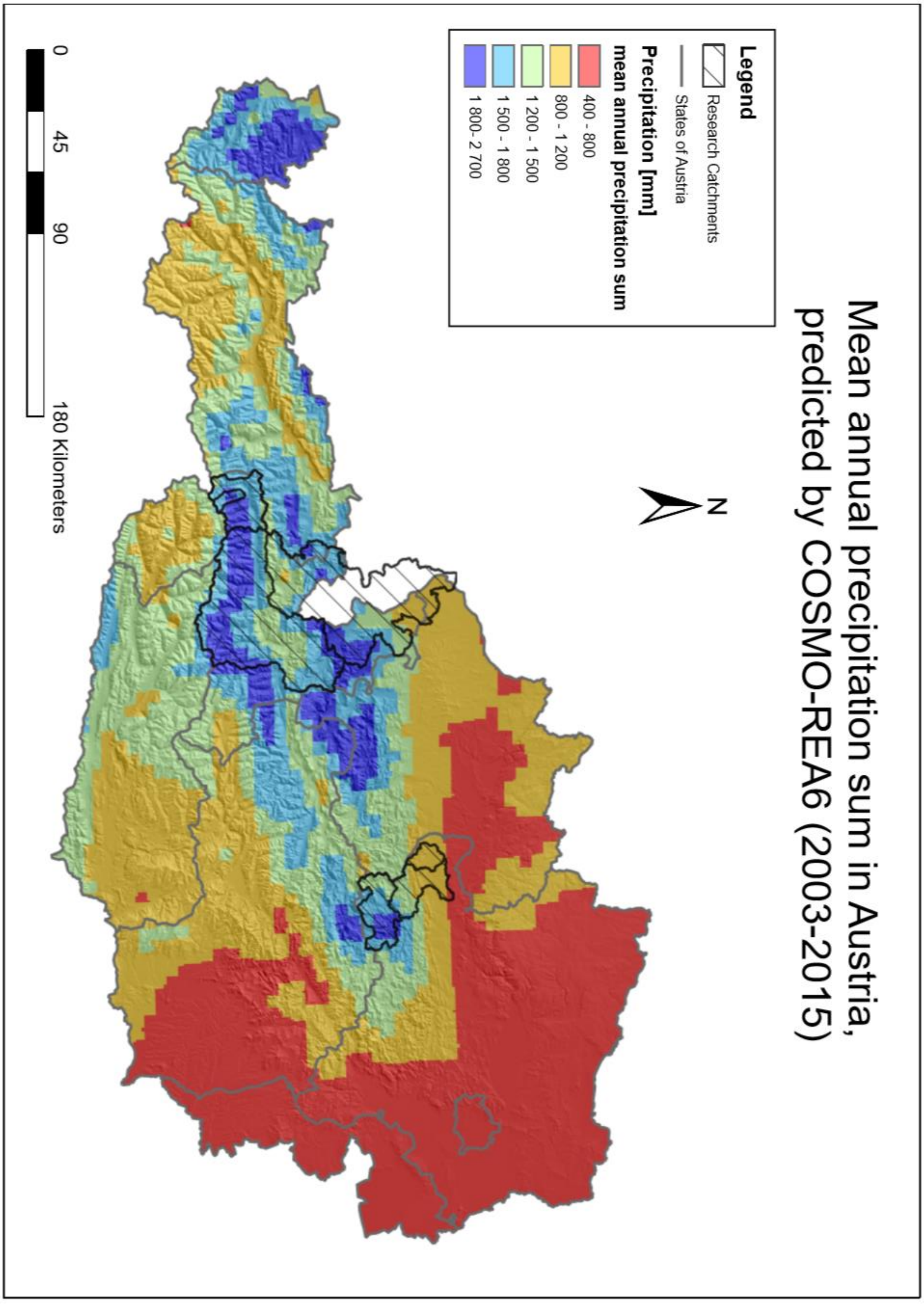

Figure 10-50: Mean annual precipitation sum in Austria, predicted by COSMO-REA6

11. Affirmation

I certify, that the master thesis was written by me, not using sources and tools other than quoted and without use of any other illegitimate support.

Furthermore, I confirm that I have not submitted this master thesis either nationally or internationally in any form.

Place, date, name surname, signature