MASTER THESIS IN ATMOSPHERIC SCIENCE WITH ORIENTATION TOWARDS CLIMATOLOGY

Mapping monthly precipitation in Sweden by using GIS

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Abstract

Spatial distribution of monthly precipitation is largely influenced by topography. This study focuses on deriving a gridded dataset of monthly precipitation from station observations in Sweden during 1961-2004, with help of topographic information. In order to study the influence of topography on the spatial distribution of precipitation, Sweden has been divided into three regions based on the large-scale setting of the geography. The influence of topography on the spatial distribution of monthly precipitation normals is obvious in southern region year round, and in summer time in northern and central regions at the 2 km resolution. Regression models have been built individually for each calendar month between monthly precipitation normals and selected topographical factors: elevation, slope, PX, PY, and distance to west coast. The models explain the spatial distribution of precipitation from 26.0% to 74.0% in southern region, from 9.6% to 65.6% in central region, and from 14.4% to 57.8% in northern region. After removing the effect of terrain height on spatial distribution of precipitation normals by using the regression model, the residuals are then interpolated onto a regular grid using three interpolation methods (IDW, kriging and cokriging). Cross-validation shows that kriging with spatially detrended residuals performs best and it has been chosen to interpolate the monthly precipitation normals during 1971-2000. Then, monthly precipitation anomalies from 1961 to 2004 have been gridded with all three methods. Co-kriging with elevation has similar performance, while IDW shows lowest skill when comparing with the results of kriging. Monthly normals for period 1971 to 2000 have been added back to the anomalies predicted by using kriging method to get the monthly precipitation from 1961 to 2004. Validation with independent observational data from 133 stations not used in the interpolation shows that interpolations with kriging method in mostly southern region and northeast part of Sweden are highly consistent with the original data, while several stations in northwest are always overestimated, which could be caused by the overestimated influence of topography. The study suggests that the Swedish precipitation distribution could be partially explained by topographical variables, especially in Southern and summer time in Central and Northern Sweden, and the kriging with detrended data can be used in gridding monthly precipitation with higher precision. All the work has been done in GIS (ArcGIS) and the final precipitation climatology has been created suing widely applied Raster and NetCDF formats, which ensures the easy application of the dataset in both climate studies and other fields.

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1. Introduction

Weather is a topic that concerns us every day and affects each one's life on the earth. Climate, which describes average weather or regular weather conditions over many years, is getting more and more important in many fields such as agriculture, ecology, forestry, health and disease, urban conditions and so on (Champman and Thornes, 2003). In many applications, precipitation and temperature are the most important climate variables, consequently those have attracted many researchers' interest.

However, many of these applications require data for points and areas for which no measurement are readily available. Climate data is frequently collected at weather stations located at irregular points. This means that the station density may vary depending on region. For instance in mountainous regions station density is often lower because it is hard to build and maintain stations here. To obtain climate information that is more continuous in space, one way is to interpolate climate data obtained at irregular points to regular grids covering a certain area of interest. Many studies exist on the issue of interpolating data from irregular points to a regular grid using different climate variables and different techniques (e.g. Hevesi et al., 1992; Goodale et al., 1998; Gooveaerts et al., 2000; Vicente-Serrano et al., 2003; Lloyd, 2005; Hofstra et al., 2008).

Once the gridded climate data is achieved, it can be used not only in historical analysis in climatology, hydrology, agriculture and some other related fields, but also to evaluate model simulations by comparing modeling results with gridded observations. Nevertheless, when trying to get regular climate data, it's essential to consider several questions first. Since this study deals with interpolation of precipitation observations, the following discussion mainly focus on issues related to precipitation.

Climatological and meteorological data distribution highly depends on local conditions, especially in regions with complex terrain (Tveito and Schöner, 2002). Precipitation distribution can be rather different from coast to inland, high altitude to low altitude, and upper slope to down slope etc. In order to improve the precision of the gridded climate data, it is essential to consider the local environment that affects the distribution of climate data first, especially topographic conditions including altitude, slope, and distance to coast.

Another issue is the choice of interpolation method. There are many different techniques available, such as IDW (Inverse Distance Weight), splines, kriging, or cokriging. The method that gives the most realistic results should be chosen to do the interpolation.

The methods mentioned above are included in standard GIS (Geographical Information System) software, such as ArcGIS. ArcGIS has very strong functions in handling data from many different sources and stored in various kinds of data formats, (e.g. the widely used climate data format NetCDF).

1.1 Aim of the study

The general aim of this study is to interpolate monthly precipitation in Sweden obtained from the irregular network of synoptic weather stations to a regular grid covering the whole country. Considering the different issues above, one of the main aims of this study is to investigate the relationship between normal precipitation and topographical parameters including altitude, slope, curvature, PX (the coordinate parameter which represents distance to Prime Meridian), PY (the coordinate parameter which represents distance to Equator), and distance to west coast. The results may help to improve our understanding of how topographical conditions influence the spatial distribution of normal precipitation.

Sweden is situated close to the Sea but partly sheltered from it by the Scandes, a mountainous area stretching in North-South direction. Comparing with most of the studies that have been done previously, the distance to coast and topography’s effect on precipitation has not been analyzed in greater detail compared to studies in other countries. Johansson and Chen (2003) analyzed distance to coast, the combined effect of slope and wind, and elevation in gridding daily precipitation in Sweden, however, their study focused on daily precipitation, and they only analyzed spatial scale 4km and 12km. The time period included in these studies is pretty short (Bergeron, 1968; Johansson, 2000; Johansson and Chen, 2003). The World Meteorological Organization (WMO) defines three consecutive decades as the length of climate normals which represents the average state of climate elements. Thus, in order to get a systematic comprehension of average precipitation of Swedish with geographical information, it’s important to investigate it in at least 30 years. In this study, the time period of precipitation ranges from 1961 to 2004. The monthly climate normals of precipitation will be calculated for 1971-2000 to get the average precipitation. The topographical variables will include elevation, slope, PX, PY, curvature, and distance to west coast. And nine different spatial scales from 50m to 20km will be analyzed in this study.

Another aim is to investigate the performance of different interpolation methods in order to find out which one works best, suitable method will increase the precision of final predictions. The performance of all three methods in interpolating monthly precipitation will also be compared.

This study will provide comprehensive monthly gridding results for the period 1961-2004, which has not been done previously for such a long time period, and examined so many different spatial resolutions, as described above. The relationship between precipitation and topography variables, such as elevation, slope, curvature and distance to coast will be studied. This may help increase the precision of interpolation results. The interpolation method which gives the most realistic results will be utilized in gridding the monthly precipitation normal and then the monthly precipitation. Finally, all the gridding procedures will be carried out using GIS. The final datasets are stored in GIS raster format facilitating the use of the final data sets in various practical applications.

2. Literature review

According to the questions discussed above, many studies related have been conducted in the past two decades. Studies about the influence of topographical variables on precipitation and comparison of interpolation methods will be discussed separately as following.

2.1 Relationship between precipitation and topographical variables

Precipitation is generally increasing with elevation. This phenomenon is generally called orographic effect. This effect has been studied in many different studies in many parts of the world (e.g. Henry, 1919; Speen, 1947; Hutchinson, 1968; Vuglinski, 1972). The process causing precipitation enhancement can according to Daly (1994) been described as follows: "*Depending on its size and orientation, a mountain or range of mountains can increase the cyclonic precipitation by retarding the rate of movement of the storm and causing forced uplift of the air mass. In summer, the orographic effect may trigger a conditional or convective instability in an otherwise stable air mass, producing a local redistribution of precipitation over the higher ground*". Regarding elevation's effect on precipitation, many studies (Hevesi et al., 1992; Daly et al., 1994; Martı´nez-Cob, 1995; Goodale et al., 1998; Goovaerts, 2000; Kyriakidis et al., 2001; Daly et al., 2003) have been conducted in the past two decades. Among them, Goodale et al. (1998) incorporated elevation with polynomial regression method to generate monthly precipitation and other climate variables in Ireland. Goovaerts (2000) proved that the correlation between monthly rainfall and elevation ranges from 0.33 to 0.83. Including terrain information into the interpolation Daly et al. (1994) derived the linear relationship between precipitation and elevation in United States, and constructed a widely applied model called PRISM (Precipitation- elevation Regressions on Independent Slopes Model).

Besides elevation, many studies have been conducted to generate relationship between precipitation and various other topographical variables. For example, when the study area is close to the Sea, relation between precipitation and distance to coast is usually considered (Yamada, 1990; Agnew et al., 2000; Weisse et al., 2001; Marquínez et al., 2003; Perry et al., 2005). For study areas located in mountainous area, the relationship between precipitation and factors such as elevation, slope, and aspect are usually considered (Basis et al., 1994; Prudhomme et al., 1998; Agnew et al., 2000; Marquínez et al., 2003). Other geographical variables, such as latitude, longitude, position or azimuth have also been involved in some studies (Ninyerola et al., 2000; Wotling et al., 2000; Naoum et al., 2004; Oettli et al., 2005; Ninyerola et al., 2007).

When the relationship between topography and precipitation is established, it can be used in model building. Many studies use stepwise regression when choosing the relevant topographical variables (Agnew et al., 2000; Ninyerola et al., 2000; Wotling et al., 2000;Weisse et al., 2001; Marquínez et al., 2003; Oettli et al., 2005). All these studies explained spatial variability of precipitation distribution to different extent.

In Sweden, the effect of topography on precipitation has also been investigated in several studies. Bergeron (1968) found large increase of precipitation over low hills, and attributed it to a seeder-feeder mechanism, which confirmed topography's effect on precipitation. Johansson (2000) found relationship between precipitation and topographic variables including elevation at least. Then, the influence of wind, both speed and direction, topography (slope) and distance to coast (DTC) on daily precipitation distribution was investigated for the period 1981-1995 (Johansson and Chen, 2003). The results showed that the location of a station with respect to a mountain range was the most important variable. Slope multiplied by wind speed was another important variable for ascending air. The effect of slope was proven to be higher for stations close to the coast. After the investigation of the influence of wind and topography's on precipitation, they interpolated daily precipitation with optimal interpolation method and also considered the influence of topography on precipitation (Johansson and Chen, 2005). When analyzing the spatial variability of meso-scale precipitation in Scania in Sweden, Linderson (2003) found that the distribution of precipitation is greatly influenced by topography, land and surrounding sea's effect was also important. All the studies above implicated the important effect of topographical variables on precipitation distribution in Sweden.

2.2 Interpolation methods comparison

An important issue in interpolating precipitation to a regular grid is the choice of interpolation method. Many studies have dealt with this question in the past two decades.

Very often, the interpolation method is pre-decided. For example, IDW was used to construct a 10-min gridded monthly precipitation totals dataset for the Greater Apline Region (GAR) from 1800-2003 (Efthymiadis et al., 2006). Another study used ordinary kriging (OK) to interpolate point precipitation into annual and seasonal maps for the Nordic region (Tveito et al., 1997). Linear regression was successfully used by Daly (1994) in building the PRISM model for interpolating precipitation. Another approach is the use of splines in combination with a digital elevation model to obtain gridded mean monthly temperature and precipitation in Alaska (Fleming, 2000). Also other methods such as neural networks have also been used for interpolation purposes, e.g. Antonic et al. (2001).

The choice of interpolation method depends on the interpolation task, the climate variable and the topographical settings of the region for which the interpolation is done. It is therefore not necessarily obvious which interpolation approach to adopt and selecting a suitable method is not always straightforward task. Many studies have dealt with the issues of comparing different interpolation approaches in the past two decades (Hevesi et al., 1992; Dirks et al., 1998; Goodale et al., 1998; Prudhomme et al., 1999; Gooveaerts et al., 2000; Price et al., 2000; Vicente-Serrano et al., 2003; Lloyd, 2005; Hofstra et al., 2008). In the following, a few relevant methods are briefly reviewed and assessed for their suitability for our study.

Inverse Distance Weight (IDW) is one of the simplest methods and is easy to understand. It is a method which utilizes the inverse of the distances between the known points and the point to be estimated. In other words, points that are close to the unknown point have greater influence than points located further away. IDW is convenient for data analysis where the station density is not too sparse. Goodale et al. (1998) compared polynomial regression and a modified IDW in generating gridded monthly precipitation for Ireland, but did not found significant differences in the results. Dirks et al. (1998) compared four interpolation methods (kriging; IDW; Thiessen; areal mean) in generating rainfall data from 30 gauges on Norfolk Island. IDW was recommended to fulfill the gridding, since it not only gave as best results, but also for its simplicity. In predicting monthly mean precipitation for Canada, Price et al. (2000) found that IDW performed equally well as thin–plate smoothing splines in region where topographic and climatic gradients are smooth.

Kriging includes many different types of algorithms, and includes terrain information such as elevation to improve the precision of estimates. Among them, the most frequently used is ordinary kriging. Ordinary kriging predicts the results in the form of a linear combination of measured values, whose weights depend on the spatial correlation between them. The biggest advantage of ordinary kriging is the estimation of kriging variance, which quantifies the uncertainty of the interpolation. The disadvantage of ordinary kriging is its prior assumption-intrinsic stationarity, which means the raw data will not change with time or space. This is rarely fulfilled. In order to compensate for the disadvantage of ordinary kriging, residual kriging and cokriging are developed. In residual kriging, a trend is subtracted from the input variables before using of ordinary kriging. The trend is usually with respect to topographical or physiographical factors. In cokriging, other co-variables such as elevation and slope are included in the establishment of the semivariogram.

These methods have been extensively used in many studies and perfomed always satisfying. When generating average annual precipitation, Hevesi et al. (1992) compared eight interpolation methods (neighborhood average; IDW; IDW squared; IDW cubed; kriging; Log-linear regression; linear regression; cokriging) and found that cokriging performed best in combined results. Prudhomme et al. (1999) proved modified residual kriging gave better precision results than ordinary kriging in estimating extreme precipitation in mountainous region in Scotland. Gooveaerts et al. (2000) also compared three geostatistical interpolation methods (simple kriging with varying local means; kriging with an external drift; and colocated cokriging) with three other univariate methods (the Thiessen polygon; inverse square distance; and ordinary kriging) in generating gridded precipitation data, and geostatistical interpolation methods were chosen for generating maps. Vicente-Serrano et al. (2003) compared global interpolators, local interpolators, geostatistical methods and mixed methods in interpolating annual precipitation data in a valley in Spain where geographic and climatic difference are significant. Their results indicated best results with geostatistical methods including many kriging and cokriging methods. Lloyd (2005) compared five interpolation methods to get monthly precipitation in Great Britain, and proved that ordinary kriging gave best results in January and February, kriging with an external drift was best for the rest time. When generating daily precipitation data in the whole Europe, Hofstra et al. (2008) compared six interpolation methods and finally chose global kriging.

In Sweden, several studies have been done in order to generate gridded precipitation maps. Tveito et al. (1997) used ordinary kriging which was pre-decided in generating annual and seasonal precipitation maps in Nordic region including Sweden. Johansson (2000) compared three different interpolation methods (Subjective selection of weights; IDW; optimal interpolation) for estimation of areal precipitation and temperature in Sweden from 1977-09-01 till 1997-08-31, and the result showed best estimation with optimal interpolation. Then, Johansson and Chen (2005) used optimal interpolation method in generating daily precipitation from 1981 to 1999 in the whole Sweden, and results were validated by cross-validation.

Besides these studies, some studies have also been done to generate girdded precipitation datasets for long time periods but without evaluating interpolation methods or the influence of topography For example, Alexandersson et al. (1991) generated precipitation normals for Sweden from 1961 to 1990 using 1243 stations. Their report (Alexandersson et al., 1991, p29) include earlier studies on this issue carried out for Sweden. Alexandersson (2002) also generated annual and seasonal temperature and precipitation maps from 1860 to 2001 in order to study the change in the Swedish climate.

The Swedish studies mentioned above lack a comparison of interpolation methods except Johansson's study (2000). However, in his study, just Scandinavian mountains area is included, and the time resolution is daily which is different from monthly resolution of this study. The study by Hofstra (2008) deals with entire Europe, and the result of the method comparison may be not valid when just considering Sweden. To get the best possible estimates of Swedish precipitation in the 40 years, it's necessary to compare several proposed interpolation methods.

Concluding from all the studies cited above, we can see that IDW is frequently used for its simplicity and efficiency. It is especially suitable for regions with rather smooth topography, e.g. Southern Sweden. Various types of kriging have also been compared with other methods and generated the best results in many studies, especially ordinary kriging in Sweden (Tveito et al., 1997). Based on the studies reviewed above, three interpolation methods will be evaluated in this study: IDW, kriging and cokriging and the one that performs best will be selected to generate normal precipitation and the monthly gridded precipitation data set.

3. Study area and data

3.1 Study area

Sweden, one of the Scandinavian countries, is located in northern Europe. Despite its northern latitude, most of Sweden has a temperate climate. The Swedish climate can be divided into three types- oceanic climate in the southernmost part, humid continental climate in the central part, and subarctic climate in the northernmost part (*en.wikipedia.org/wiki/Sweden*). Due to Scandinavia's vicinity to the warm Gulf Stream, the climate of Scandinavia is much warmer than the climate of Greenland which is located equally far north (Raab et al., 1995). The topography of Sweden various considerably from south to north, with major plains and low lands in the south part, and high mountainous area in the north-west part. The elevation of Swedish landscape ranges from 0 to 2098 m (from DEM data with 50 m spatial resolution). Sweden is separated from Norway with Kjolen Mountain range, and the highest point of Sweden, Mt. Kebnekaise, lies on this range. North-west Sweden is hard to build climate stations, so it's important to get interpolated precipitation data for these areas' study. Due to the long distance in north-southern direction, Sweden will be divided into several districts and studied separately.

3.2 Data

3.2.1 Instrument data

The data used in this study is based on daily station data for the period 1961 to 2008 provided by SMHI (Swedish Meteorological and Hydrological Institute). There are 1977 stations totally. The monthly precipitation was derived from the daily data. The location of the stations is given in RT 90 which is a local projection method of Sweden. Information about relocation of stations is also available.

During these 49 years from 1960 to 2008, the number of stations was varying as new stations were established or existing ones closed. In Figure 1, the number of stations together with the amount of missing data (MD) for different time periods is described.

When interpolating monthly precipitation normals, the number of stations shown by the solid line (missing data is less than 5 years from 1971 to 2000) has been chosen. The total amount of stations is 522, and the location of the 522 stations can be seen in Figure 2. Since normals is an average state of climate dataset, the missing data should be controlled to minimize the errors.

There is a gap of the number of station available between 1960 and 1961. 30 stations will be included in interpolation due to the starting date of the observation is 1961. When interpolating monthly precipitation, the number of stations shown by the dotted line (missing data is less than 5 years from 1961 to 2004) has been chosen to keep the consistency of the results. So the monthly precipitation will be interpolated from 1961 to 2004. This will also keep the precipitation data as a continuous dataset. The gridded data can be used in climate change study.

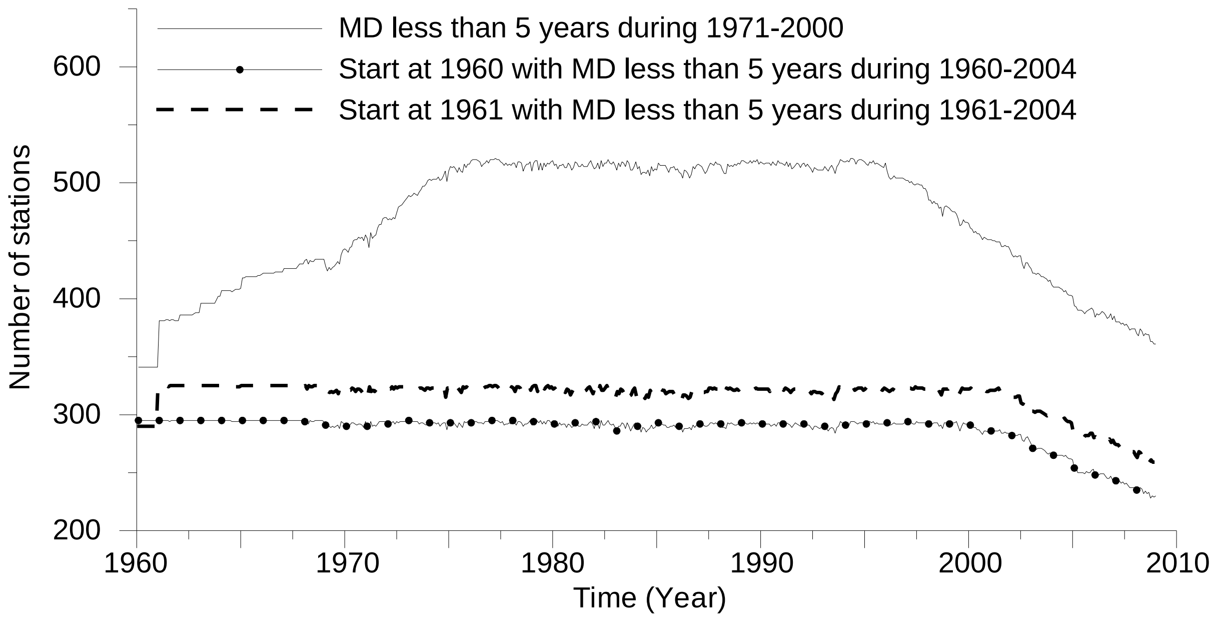


Figure 1 Number of precipitation stations in Sweden from 1961 to 2004.

3.2.2 DEM data

Digital elevation model (DEM), also known as digital terrain model (DTM), is a digital representation of the surface topography. Based on the DEM shown in Figure 2, various kinds of topographical variables, such as slope, aspect, curvature etc, can be computed. The DEM data used in this study covers almost the whole Sweden with 50m spatial resolution, and it is downloaded from Digitala Kartbiblioteket (*https://butiken.metria.se/digibib/index.php*). The DEM is spatially referenced using the national Swedish grid RT90. Even though the grid SWEFEF99 recently replaced RT90, the latter is still used in this study to maintain georeferencing consistency between all data sets used. From the DEM, elevation, slope, curvature, and distance to west coast will be computed.

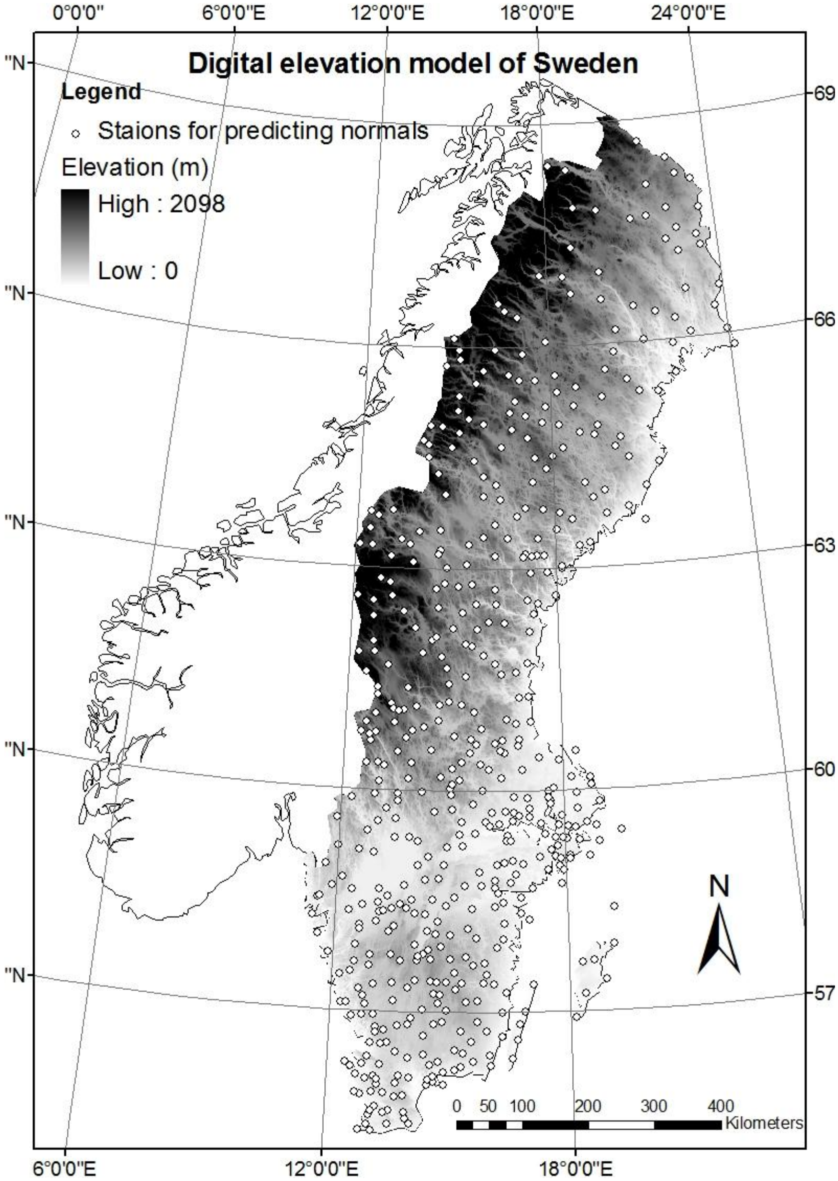


Figure 2 Digital elevation model of Sweden

4. Methods

This section describes district division, preprocessing of the data, including the selection of geographical variables, the construction of the relation between monthly mean precipitation and geographical variables, the interpolation methods to be compared, the application of GIS, and the main workflow of the work.

4.1 District division

The study area has been divided into three regions based on the distance to the west coast and the elevation data. Since the majority of the weather systems are approaching Scandinavia from westerly directions, distance to coast is always calculated as the distance to the west coast. As shown in Figure2, to the south of 60 °N, the distance to the coast can be computed using the coastline of Sweden. From around 60 °N, the distance to the coast is the distance to the west coast of Norway, which increases the distance to the coast significantly. Around 63 °N, although the coastline is still the west border of Norway, the distance decreases again. To the south of 60 °N, the elevation is pretty low compared to the area north of 60 °N, and the mountainous area of Sweden is mostly located to the north of 63 °N.

Combining all the information above, the two latitudes 60 °N and 63 °N are chosen to divide the study area into three sub-regions. The sub-regions are: Southern region (South of 60 °N), Central region (60 °N-63 °N), and Northern region (North of 63 °N). The data in each area will be studied separately.

4.2 Preprocessing of data

4.2.1 Pre-handling of DEM data

In the DEM data for several points in the south were found missing. To keep the continuity of the height information and other geographical variables based on the DEM, the missing points were interpolated by using neighborhood values, and then added back to the original DEM data. The tool used here is *Merge* included in the standard toolbox Map Algebra of ArcGIS.

4.2.2 Computation of topographical variables

The original spatial resolution of the DEM is 50m. Topographical variables (slope, aspect, and distance to west coast) could simply be calculated at this resolution; however, the 50 m resolution does not necessarily be the most appropriate resolution for relating precipitation to topographical conditions. The reason is that the effect of topography on rainfall may be most obvious at a resolution that is coarser than the original one when small-scale features are left out to some extent. For instance coarse resolution smoothes terrain height with regard to peaks and dips, and consequently impacts the calculation of slope and aspect. Depending on resolution, the geographical information for the same station, for example altitude, varies. In order to find a best spatial scale to reflect the influence of topographical variables on precipitation, the topographical variables have been calculated for the following scales: 50 m, 100 m, 200 m, 400 m, 1 km, 2 km, 4 km, 10 km, and 20 km, and geographical variables will be computed based on them.

From these scales, the scale that gives the best correlation between the original normal precipitation data and elevation, slope, and curvature with will be identified and used in the interpolation. Distance to west coast is computed in DEM just with 50 m, since scale doesn't affect distance so much. PX and PY are also included in the topographical variables, which will give the influence of position on precipitation. PX is the coordinate parameter representing the distance to the Prime Meridian, and PY is coordinate parameter representing the distance to the Equator. These two parameters are defined in the mathematically way in this study and are opposite to the convention of denoting coordinates in RT-90, where X denotes latitude and Y longitude.

All these works will be done in ArcGIS, resample and surface tools will be used.

4.3 Stepwise regression

As mentioned before, stepwise regression have been used in choosing relevant topographical variables in many studies (Agnew et al., 2000; Ninyerola et al., 2000; Wotling et al., 2000;Weisse et al., 2001; Marquínez et al., 2003; Oettli et al., 2005). The same method will be used to examine the relationship between normal precipitation and geographical variables. In this step, 30-year mean monthly precipitation data (1971-2000) will be chosen, since it represents the average states of precipitation in Sweden. For each calendar month, the relationship between normal precipitation and topographical variables will be examined. The relationship built from the time period should be representative in Sweden.

Software SPSS (Statistical Package for the Social Sciences), a computer program for statistical analysis, will be used to study the relationship. There are many geographical variables in this study, including elevation, slope, distance to west coast, PX, PY, and curvature. Stepwise regression will be used in choosing the most related variables. Stepwise regression starts from one variable, and adds one more variable in each step. While adding the new variable, the algorithm examines each variable in the regression to judge whether the new variable is significant. All significant variables will be kept and entered in the next step. The significance level used in this study is $t_{0.05}$.

After the regression step, the variables satisfy the requirement will be used in single or multiple regression analysis to construct the model.

Depending on the outcome from the regression analysis step, one or more variables are kept, i.e., the model may either be based on single or multiple regression.

4.4 Interpolation methods and cross-validation

Three methods, IDW and Ordinary kriging are compared in this study to interpolate the detrended residuals, and cokriging to interpolate the original normal precipitation. Cross-validation will be used to identify the method that performs best. Based on the result of this comparison, the method that gives the best precision will be used to interpolate the precipitation residuals.

Mathematical details about the three methods are described in the following. Further information about interpolation methods in climatological and meterological field can be found in Tveito (2002) and Dobesch (2001).

4.4.1 IDW

IDW is an advanced nearest neighbors method which utilizes the distance from the measured points to the unknown point to decide the weight of the different measured points. The closer the station is located to the unknown point, the higher weight it gets (Tveito, 2002). Weighting power P can also be used to raise the distance weight, P ranges from 0 to 2. In this study, the power P is pre-decided as 2.

Normally there are two principles to decide the amount of points to be included. In one case, one simply decides the amount of the stations. Another way is to set the distance to the predicting point, and stations that are located within this distance will be included in the computation.

The mathematical function of IDW is as following:

$$Z_j^* = \frac{\sum_{i=1}^{n} \frac{Z_i}{h_{ij}^{\beta}}}{\sum_{i=1}^{n} \frac{1}{h_{ij}^{\beta}}}$$

where

Z_j^* is the estimated value in point j;

Z_i is the value in point I;

i is the index (coordinate) for the neighboring points;

j is the index (coordinate) for point to be estimated;

h_{ij} is the distance between point to be estimated j and neighboring points I;

β is the weighting power.

4.4.2 Ordinary kriging

Ordinary kriging, the most commonly used type of kriging, predicts the results in the form of a linear combination of measured values, whose weights depend on the spatial correlation between them. The sum of weights equals to 1. The prior assumption of this method is that the spatial process must be assumed as intrinsic stationarity, which means the raw data will not change with time or space. The process to transform the raw data to intrinsic stationary is usually referred as de-trending (*http://en.wikipedia.org/wiki/Stationary_process*). The need of intrinsic stationarity is also the disadvantage of this method, since there's rarely intrinsic stationary random process in meteorological variables. So, residual-kriging is usually used to compensate the disadvantage of this method. The mathematical function for ordinary kriging is as following:

$$\hat{Z}(s_0) = \sum_{i=1}^{n} w_i Z(S_i)$$

Where

$\sum_{i=1}^{n} w_i = 1.$

The value of w_i can be derived from function $E((Z(S_0) - \hat{Z}(S_0))^2 = \text{Minimum}_{w_{i\,(i=1,\ldots n)}}$

4.4.3 Cokriging

Cokriging, which allows the input of multiple variables to generalize better gridding results, is an extension of kriging. Cokriging estimates the cross-variogram of two different variables, which is a function related to their distance difference. "Cross-variogram analysis is a spatial analysis technique in which two variables are used with the aim to examine the spatial co-structure occurring between them"(Rossi et al., 1995). When the value is minus, the changing direction of the two variables is opposite, otherwise the direction is the same. When the value equals to zero, two variables are independent to each other. The mathematical form of cross variogram is shown as following:

$$\gamma^k(h) = \frac{1}{2n}\sum_{i=1}^{n}[z(x_i) - z(x_i + h)][z^k(x_i) - z^k(x_i + h)]$$

Where

$z(x_i)$ is the prediction, k is the number of the variable, h represents the distance between them.

Cokriging is mainly motivated by the cases when the main variable is under- sampled. The under-sampled location can be compensated by the auxiliary variables. The difference between kriging and cokriging is whether data cover all variables at all sample locations and whether variables are intrinsically correlated, if so, cokriging is equal to kriging (Tveito, 2002).

When referring to more than one variable, cokriging becomes to be very complex, detail information about this method can be found in Cressie (1991).

4.4.4 Correlogram

Correlograms are used to find the searching distance used in an interpolation. When estimating the precipitation value for an unknown location, the closer the measured station is, the larger the influence is. There should be one distance (range) beyond which the influence drops to zero with increasing distance. Only stations located in this extent will be used to predict the precipitation. This distance can be used in comparing different interpolation methods.

The experimental correlogram (Pannatier, 1996) for a separation vector h is calculated according to the following formula:

$$\rho(h) = \frac{C(h)}{\sigma_{-h}\sigma_{+h}}$$

Where C(h) is the covariance for the separation vector h,

$$C(h) = \frac{1}{N(h)}\sum_{i=1}^{N(h)} z(x_i) * z(x_i + h) - m_{-h} * m_{+h},$$

$$\sigma_{-h}^2 = \frac{1}{N(h)}\sum_{i=1}^{N(h)} z^2(x_i) - m_{-h}^2,\ m_{-h} = \frac{1}{N(h)}\sum_{i=1}^{N(h)} z(x_i),$$

$$\sigma_{+h}^2 = \frac{1}{N(h)}\sum_{i=1}^{N(h)} z^2(x_i + h) - m_{+h}^2,\ m_{+h} = \frac{1}{N(h)}\sum_{i=1}^{N(h)} z(x_i + h).$$

When the separation vector h is null, this expression yields 1. Note also that the value of this measure of spatial continuity is always between 0 and 1.

Since the rescaling term is the product of two different lags standard deviations, this measure of spatial continuity is also refered to as the nonergodic correlogram.

The correlogram is symmetric in h:

$$\rho(h) = \rho(-h)$$

For and omnidirectional measure, that is, a directional variogram with an angular tolerance of 90°, the standardized variogram and the correlogram are linked according to the following equation:

$$\rho(h) = 1 - \gamma_S(h)$$

4.4.5 Cross-validation

To evaluate the interpolation results of the normals for the period 1971 to 2000, cross-validation is used. The method compares measured and predicted values for all the stations. The main idea is removing one data at a time and predicting the associated data value, until all the data has been removed. The cross-validation gives error for each point. From the error, the mean absolute error (MAE), Bias, and Root Mean Square Error (RMSE) can be computed. Combined with the correlation coefficient, the method with lowest error and highest correlation coefficient will be chosen to fulfill the interpolation. The mathematical formula for each parameter is described in the following.

MAE (Mean Absolute Error)

$$MAE = \frac{1}{n}[\sum_{i=1}^{n} \left| P_{obs}^{i} - P_{int}^{i} \right|]$$

Where

n represents the number of stations, P_{obs}^{i} represents observed value, and P_{int}^{i} represents interpolated value.

Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_{obs}^{i} - P_{int}^{i})^2}{n}}$$

Bias

$$Bias = \frac{1}{n}[\sum_{i=1}^{n} (P_{obs}^{i} - P_{int}^{i})]$$

Pearson correlation coefficient (r)

If there are two variables as following,

$$x_1, x_2, \ldots, x_n$$

$$y_1, y_2, \ldots, y_n$$

Then, the function of correlation coefficient r is:

$$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})} \sqrt{\sum_{i=1}^{n} (y_i - \bar{y})}}$$

Where

$\bar{x}$ represents the average of variable x, and $\bar{y}$ represents the average of variable y.

Here, t-test is used to check whether r is significant or not. Assume $H_0: \rho = 0$, so,

$$t = \sqrt{n-2}\frac{r}{\sqrt{1-r^2}}$$

Set the obvious level as α, if $t > t_\alpha$, we refuse the assumption and consider r is significant.

In this study, α is set to 0.05.

With these statistics above, the agreement between interpolated and observed values can be quantified and the best method among the three methods for interpolating precipitation can be found.

4.5 Application of Geographical information system (GIS)

GIS is a system designed to store, manipulate, analyze, and output map-based, or spatial information (Steinberg et al., 2006). The first GIS software- CGIS (Canadian GIS) was constructed in 1963, GIS developed fast and has been used in many fields other than geography. "……GIS does the weather……" (Shipley, 1996) point out that GIS software can deal with questions in weather systems.

GIS software has been used in many meteorological and climatological applications where the task was to interpolate precipitation (Stolbovoi etc, 1998; Tveito et al., 2001, and 2005; Tsanis and Gad, 2001; Akinyemi and Adejuwon, 2008). Many interpolation methods are already available in GIS software. For example, ArcGIS supports IDW, kriging, cokriging, spline, trend, global and local polynomial interpolation and so on. ArcGIS also supports VBA (Visual Basic for Applications), python etc. script programming, which save time to handle large amount of data. Also in this study, GIS was considered as a helpful tool to accomplish the interpolation and evaluation task as well as to present and store the final result. It's also meaningful to share the datasets with other professions by means of GIS, since GIS data formats are widely used.

4.6 Workflow of the study

The main workflow of this study is as following:

- Resample DEM data and compute topographical variables.

- Step-wise regression to generate the relationship between original normal precipitation and topographical variables to construct the regression model. The data used here is from 1971 to 2000.
- Detrend the original normal precipitation data (1971-2000) with the regression model to get the residual to be used in IDW and ordinary kriging. And original normal precipitation combining with information of topographical variables will be used in cokriging.
- Compare the interpolation methods and choose the method based on the outcome of the cross-validation to interpolate the monthly precipitation normals.
- Add the trend back to the interpolated detrended residuals to get the precipitation normals for each month.
- Using the original monthly normals (1971-2000) minus the originally measured monthly precipitation data (1961-2004) and get monthly anomaly.
- Use the monthly precipitation anomaly to construct 12 variograms for every calendar month.
- Interpolate the monthly precipitation anomaly with same interpolation method as used for the residuals for 1971-2000.
- Add the gridded normals data for the period (1971-2000) back to the interpolated anomalies to get the final interpolated monthly precipitation data set.

- Obtaining monthly precipitation from 1961 to 2004 using kriging and interpolating anomalies with IDW and cokriging. Comparing the results of gridded monthly precipitation of IDW, cokriging with kriging.
- Using several stations that have not been used in all the interpolations, and validate the precision of the gridding precipitation.

5. Results

5.1 Relation between precipitation and topographical variables

5.1.1 Correlation coefficient and spatial resolution for the interpolation

The correlation coefficient (R) between topographical variables and original normal precipitation are shown from Figure 3 to 8 describing the Northern, the Central and the Southern region separately. Each figure shows the correlation in the 12 calendar months. The number of stations used is 144 for the Northern region, 114 for the Central region, and 266 for the Southern region.

In the following figures, ELEV represents elevation, and SLP represents slope. Each line represents the correlation at a certain spatial resolution. This is indicated by the number after each variable. The unit is meter and K means kilometer.

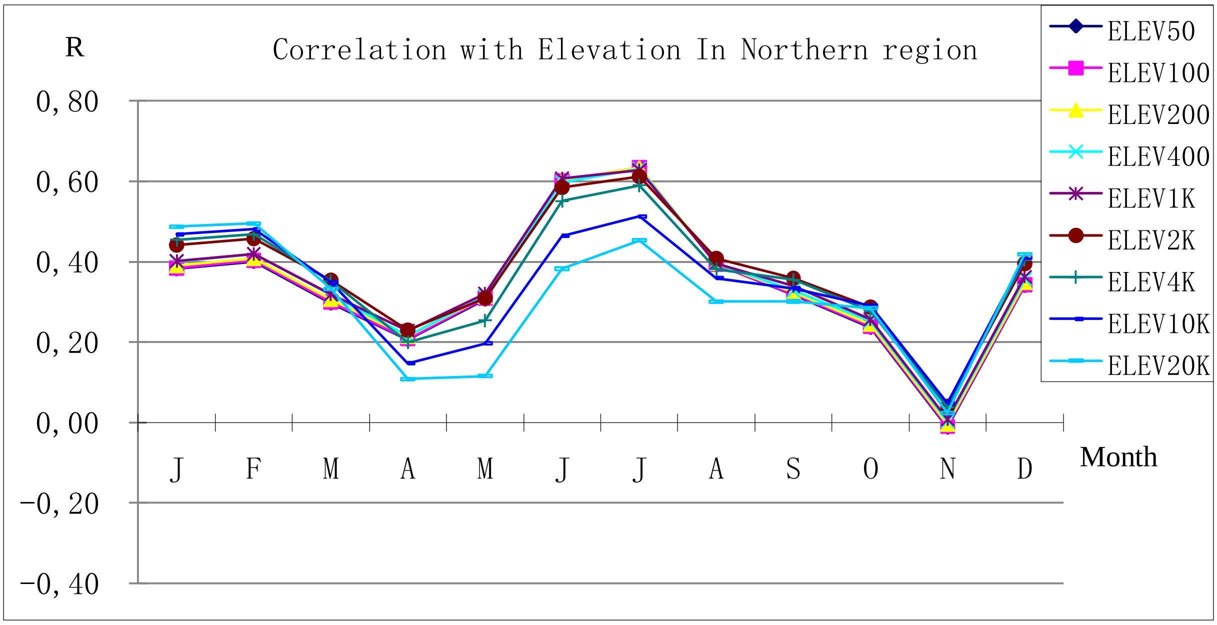


Figure 3 R values between elevation and original normal precipitation (Northern region)

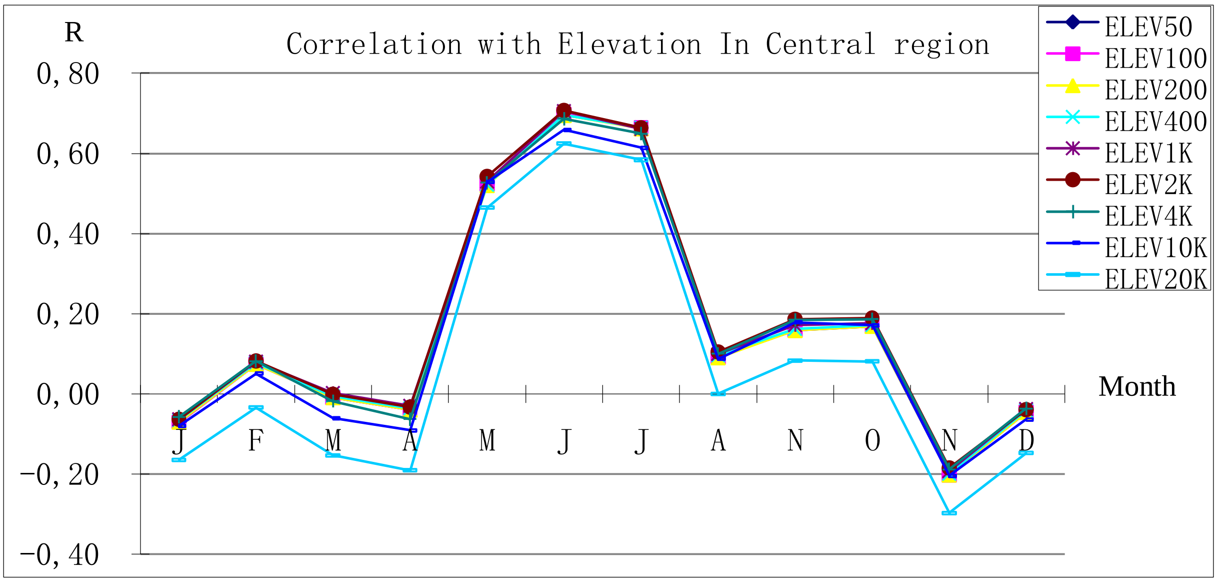


Figure 4 R values between elevation and original normal precipitation (Central region)

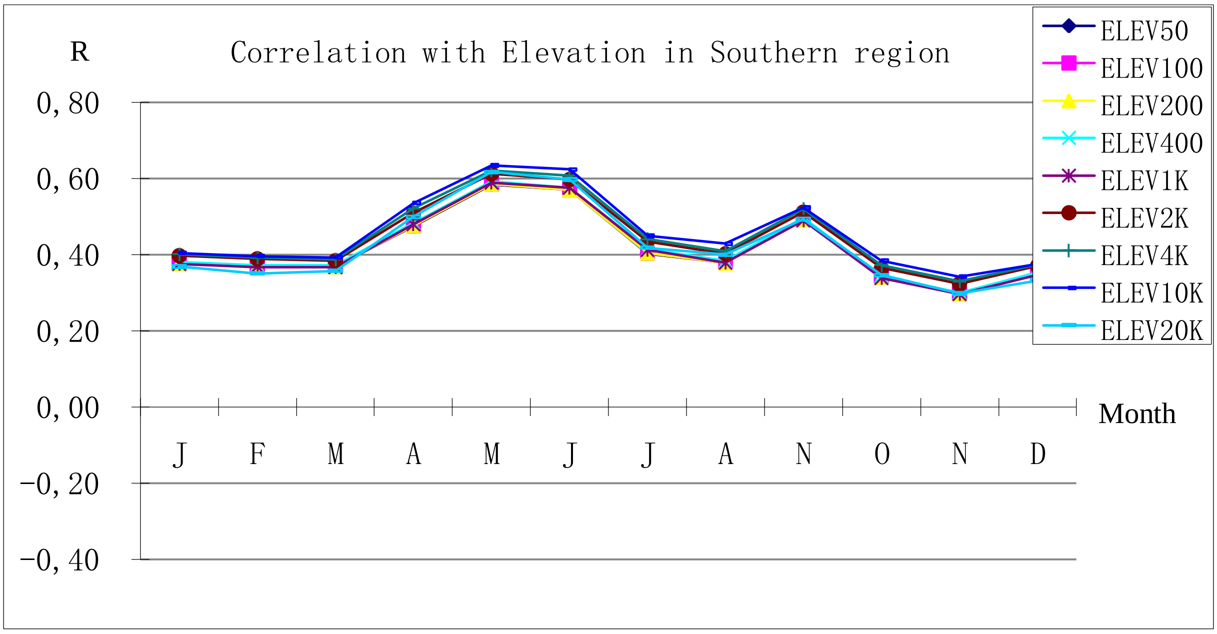


Figure 5 R values between elevation and original normal precipitation (Southern region)

As shown in Figure 3 to Figure 5, there is a clear seasonal pattern in the relation between original normal precipitation and elevation in all regions. During summer time, the correlation is higher than during winter time. Different spatial resolutions show similar patterns.

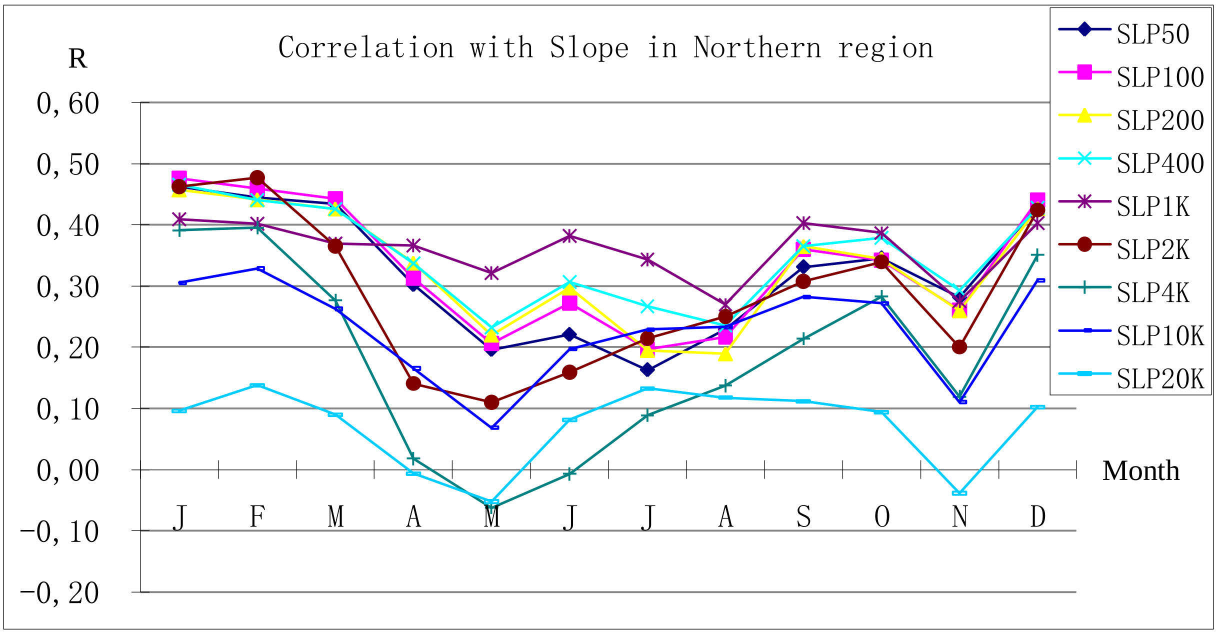


Figure 6 R values between slope and original normal precipitation (Northern region)

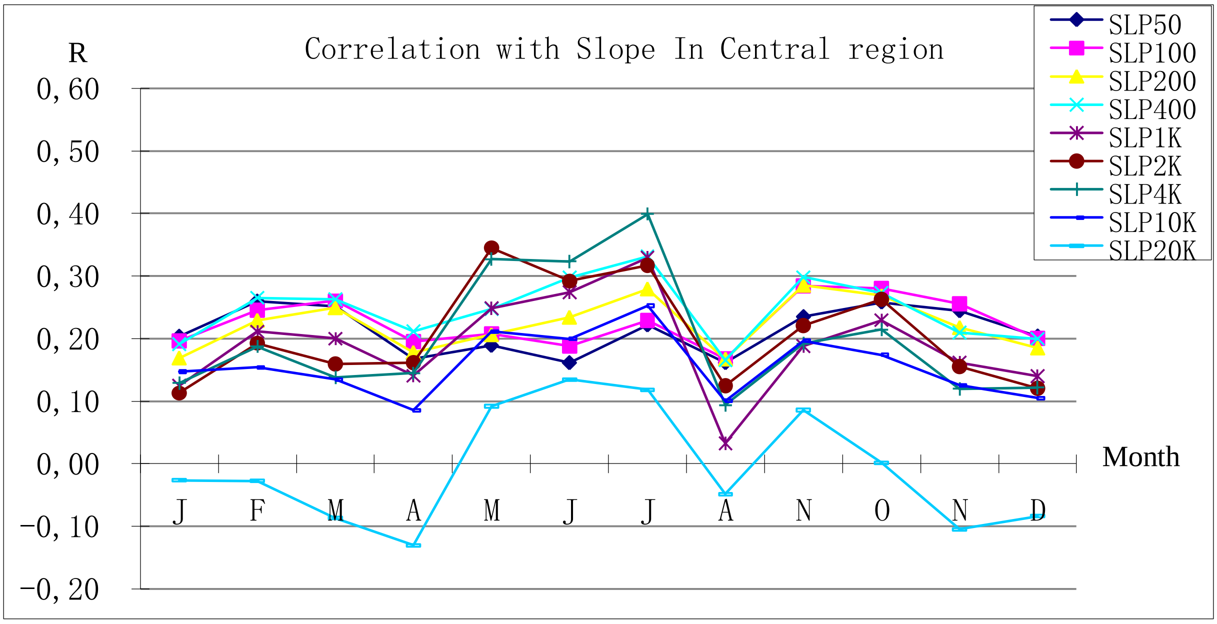


Figure 7 R values between slope and original normal precipitation (Central region)

As shown in Figure 6 to Figure 8, slope shows similar trend with respect to different resolutions. The correlations are quite stable over the course of the year in both the Southern and the Central region, while the correlation changes much in Northern region. Precipitation in the Northern region is highest correlated to slope at 1km resolution, which is affected by the mountainous area, while the Southern and Central region both shows higher correlation with 2km resolution. Normal precipitation correlates best with slope at 20km resolution in the Southern region. Differences in the scale at which correlation is highest reflects the general differences in topography in the three areas: the Northern region has the most heterogeneous topography while Southern Sweden is characterized by a much flatter topography.

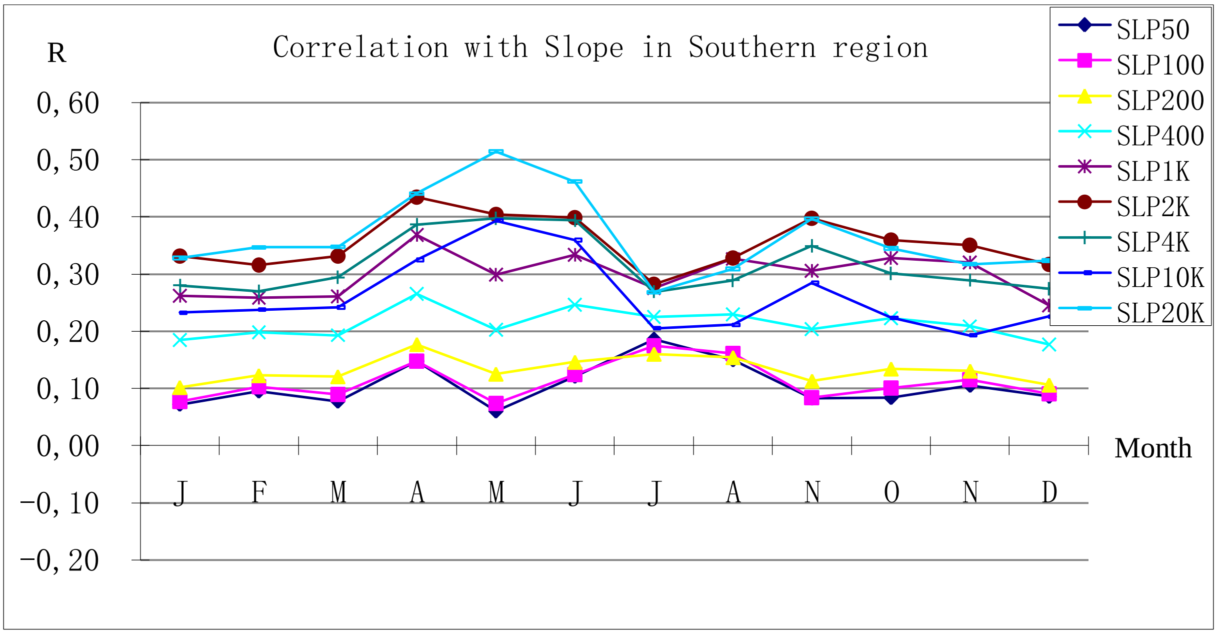


Figure 8 R values between slope and original normal precipitation (Southern region)

Curvature has also been correlated but the results show low and unstable relation (not shown here). Depending on scale, the correlation coefficients between curvature and precipitation changes between positive and negative. Comparing with curvature, the relations between precipitation and elevation and slope are more stable.

When comparing the most related spatial scale of elevation and slope, each district shows different results. In the Northern region, elevation at 2 km shows best relation in 5 months, while slope at 1 km shows best relation. In the Central region, elevation at 2 km shows best relation in 7 months, elevation at 4 km resolution is best during 4 months, and elevation at 20 km show highest correlation in 5 months. However, the other months with elevation at 20 km scale show very low relation. Slope in the Central region shows best relation in 400 m. In the Southern region, the relation with elevation is similar at 10, 2 and 4 km resolution. Regarding slope, correlation is highest for the resolution at 20km during 8 months and highest for the resolution at 2km during 6 months.

The figures above show that there is no single resolution that is obviously best for the relation between normal precipitation and topography. When considering the whole study area, the resolution at 2 km does give better relation than other scales. Therefore the spatial resolution for the final gridded datasets is set to 2 km. The overall correlation coefficient between normal precipitation and PX, PY, elevation in 2 km, slope in 2 km, and distance to west coast in each region can be found in Figure 9 to 11.

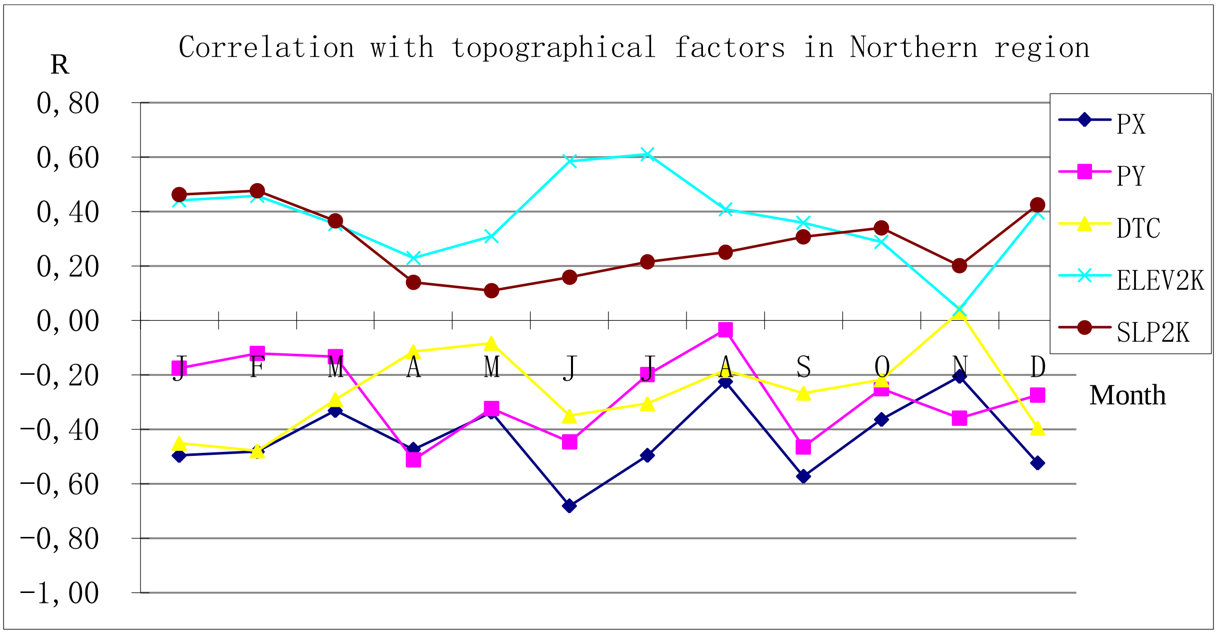


Figure 9 R values between topographical factors with 2 km resolution in Northern region

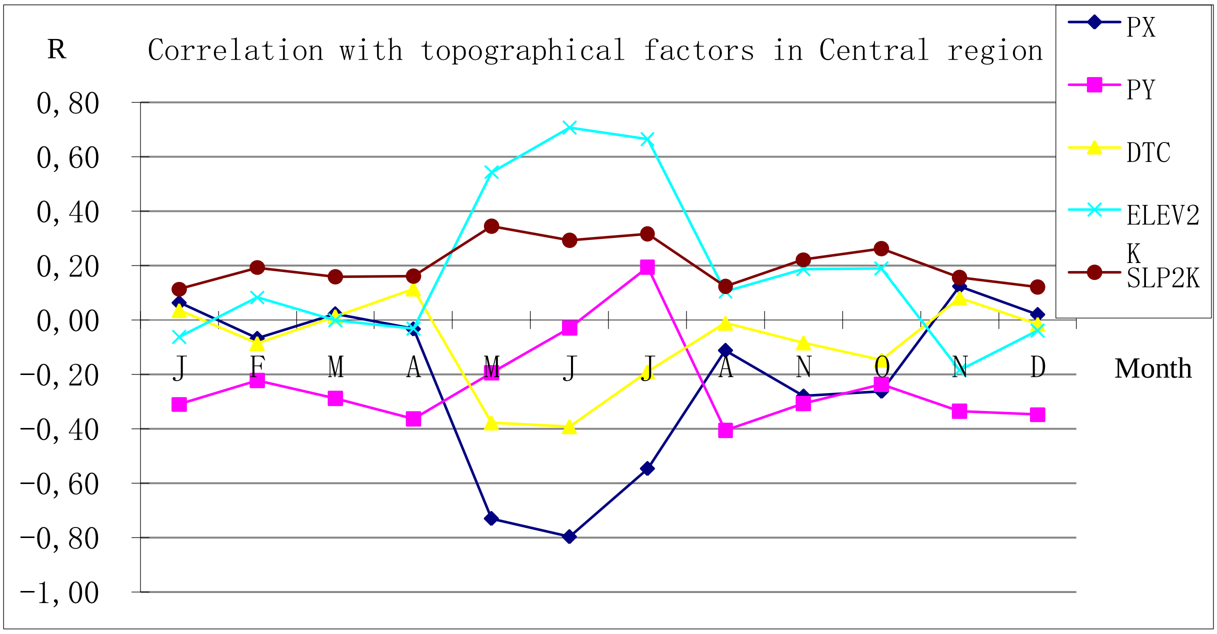


Figure 10 R values between topographical factors with 2 km resolution in Central region

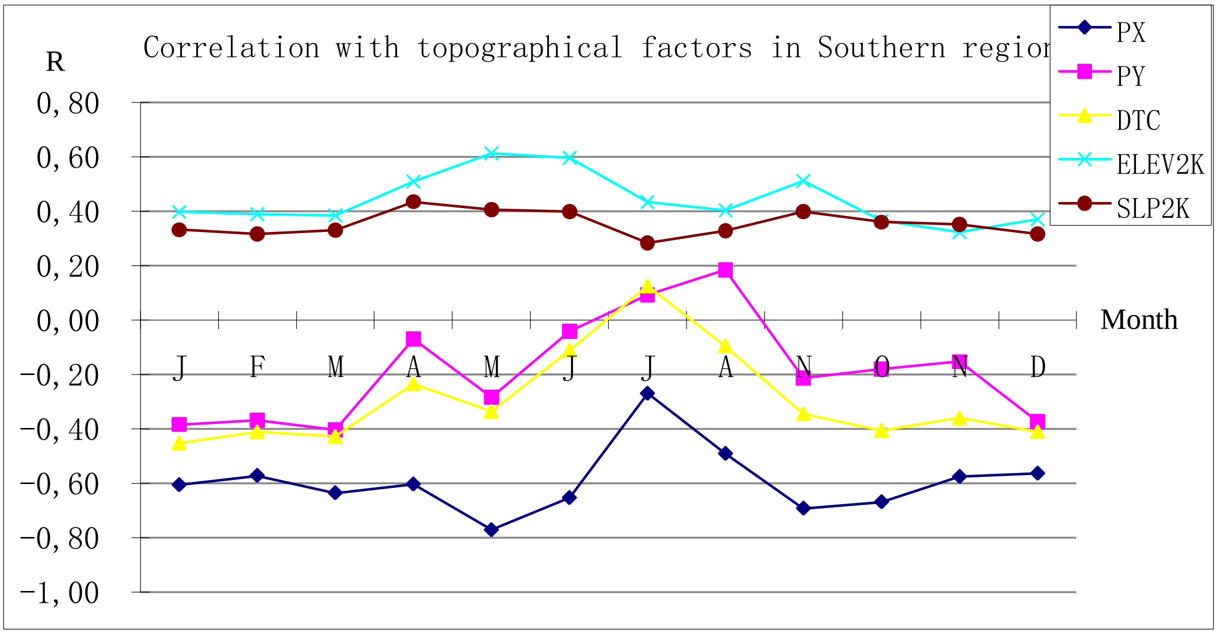


Figure 11 R values between topographical factors with 2 km resolution in Southern region

In the above figures, PX is the coordinate parameter representing distance to Prime Meridian, and PY is coordinate parameter representing distance to the Equator. DTC means distance to west coast. From the figures we can see that normal precipitation generally decreases with the increasing distance to west coast, and PX shows similar relation. Normal precipitation is increasing with increasing elevation and slope in all three districts. Of all parameters, the relation between normal precipitation and PY is weakest. PY is negative related with normal precipitation in most months, which may indicate that normal precipitation decreases from south to north. However, R value is quite low, the relation cannot explain the precipitation distribution from south to north in to a high degree.

5.1.2 Regression functions between topographical variables and precipitation

In the next step the relationships between precipitation and topographical variables are established with stepwise regression method. This gives the functions that describe the precipitation trend for each month with corresponding correlation coefficient. The relation is shown in table 1, 2, and 3 for the Northern, the Central and the Southern regions separately.

Table1. Stepwise regression with various variables and associated R values for the Northern region.

Mon	PX	PY	DTC	ELEV2K	SLOP2K	B-VALUE	R
J	-5.31E-05				6.19	126,49	0,58
F	-3.82E-05				5.08	91,40	0,58
M	-1.75E-05				2.95	61,11	0,42
A		-2.24E-05		0.011		190,90	0,57
M	-1.86E-05		0.012			64,60	0,38
J	3.54E-06	-2.74E-05		0.035		239,97	0,76
J	-2.33E-05		0.067	0.061		85,30	0,7
A			0.029	0.032		55,74	0,46
S	-3.05E-05	-2.32E-05			2.85	275,34	0,62
O	-1.40E-05	-1.82E-05			4.68	207,16	0,45
N	2.11E-05	-3.99E-05			4.40	304,75	0,45
D	-5.38E-05				4.55	128,98	0,58

Table2. Stepwise regression with various variables and associated R values for the Central region.

Mon	PX	PY	DTC	ELEV2K	SLOP2K	B-VALUE	R
J		-2.45E-05				208,86	0,31
F		-1.52E-05			1.98	131,71	0,32
M		-2.18E-05			2.07	181,14	0,36
A		-3.05E-05	0.019		2.66	241,90	0,48
M	-8.23E-05	-2.31E-05	0.024			316,23	0,79
J	-1.01E-04		0.023			210,77	0,81
J			0.015	0.029	1.76	66,63	0,7
A		-5.16E-05	0.033	0.022		411,16	0,57
S		-4.53E-05		0.017	3.08	370,68	0,5
O		-4.45E-05		0.017	4.27	354,14	0,46
N	2.60E-05	-4.54E-05			4.90	325,45	0,44
D		-3.34E-05			2.34	272,77	0,39

Table3. Stepwise regression with various variables and associated R values for the Southern region.

Mon	PX	PY	DTC	ELEV2K	SLOP2K	B-VALUE	R
J	-6.00E-05		-0.038	0.059		139,13	0,68
F	-3.95E-05		-0.023	0.040		94,15	0,64
M	-5.31E-05	-1.54E-05		0.033		215,40	0,68
A	-3.65E-05	9.56E-06		0.032		28,00	0,71
M	-4.41E-05			0.041		101,79	0,86
J	-5.91E-05	1.82E-05		0.059		25,11	0,8
J	-2.90E-05		0.027	0.050		103,17	0,51
A	-6.05E-05	3.54E-05		0.036		-78,17	0,69
S	-7.61E-05			0.061		176,86	0,75
O	-8.15E-05		-0.017		9.47	180,19	0,69
N	-6.87E-05		-0.018		11.12	163,82	0,61
D	-6.05E-05		-0.035	0.058		149,22	0,63

The results from the stepwise regression shown in the tables above are in the following used to remove the influence of topography on original normal precipitation. After detrending precipitation residuals are obtained:

$$P^{*} = P - a_0x_0 - a_1x_1 - a_2x_2 - b$$

Where

P represents original normal precipitation, P^{*} represents the residual after detrending,

a_0 , a_1 , a_2 , and b represent the regression constant, x_0 , x_1 , and x_2 represent different topographical variables used in the regression.

After subtracting the trends from normal precipitation, the residuals are interpolated with different interpolation methods.

5.2 Interpolation methods comparison

In this study, several interpolation methods were chosen and compared against each other. These are IDW, kriging and cokriging. Interpolation using IDW and kriging is done both on the original normal precipitation (Avep) and on the detrended residuals (DT). Comparing interpolation results on original and detrended data shows the difference caused by influence from topography. When detrending, single variable (1V) and multi-variables (MV) topographical factors are also compared in both IDW and kriging methods to check whether the combination of variables will improve the precision. For cokriging method, both 1V and MV for original average precipitation are compared. When interpolating residuals (DT), the trends need to be added back to get the total precipitation for each month.

5.2.1 Correlogram computation

The following six figures show correlograms separately for each of the three regions. Figure 12 to 14 show correlograms for detrended residual precipitation, Figure 15 to 17 are the correlograms for original monthly precipitation. Correlograms are computed to find the searching distance to be used in interpolation methods comparison. In the following figures, the vertical axis represents the correlogram which show the relation between unknown location and station data, and the horizontal axis represents the distance between them. With increasing distance, the relation decreases. When the correlogram is equal to zero, there is a corresponding lag distance. The stations that are located at this distance or are further away than the distance have no influence on the unknown point.

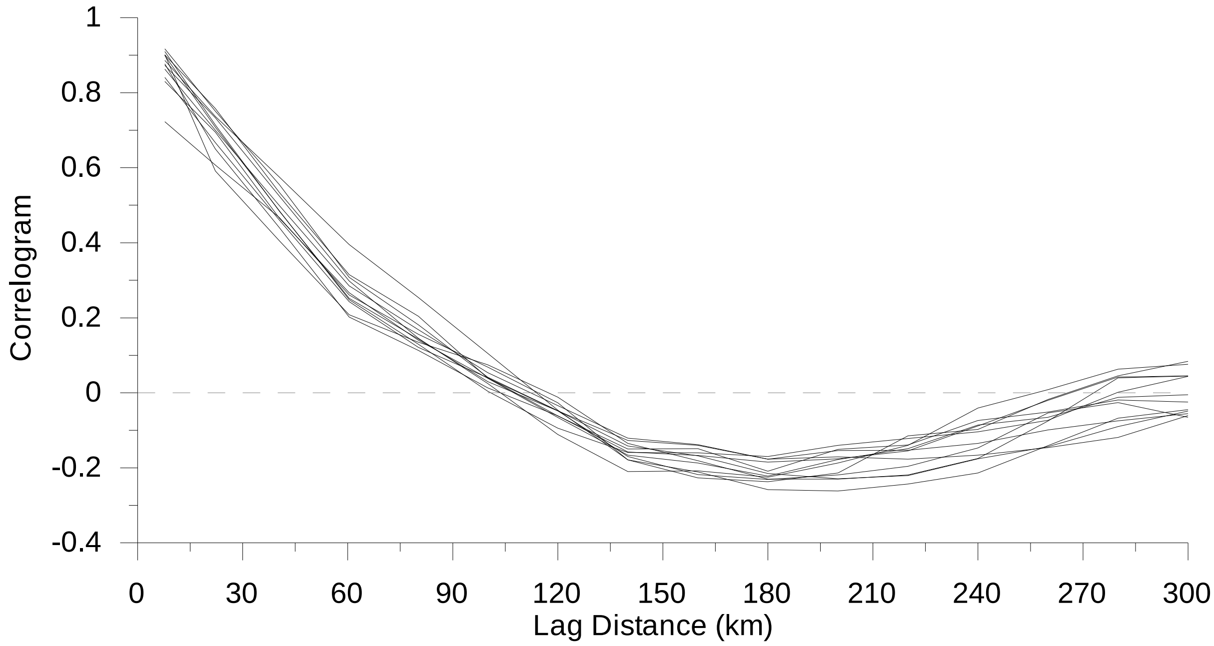


Figure 12 Monthly Correlogram based on multi-variables detrended monthly precipitation normals for Southern region

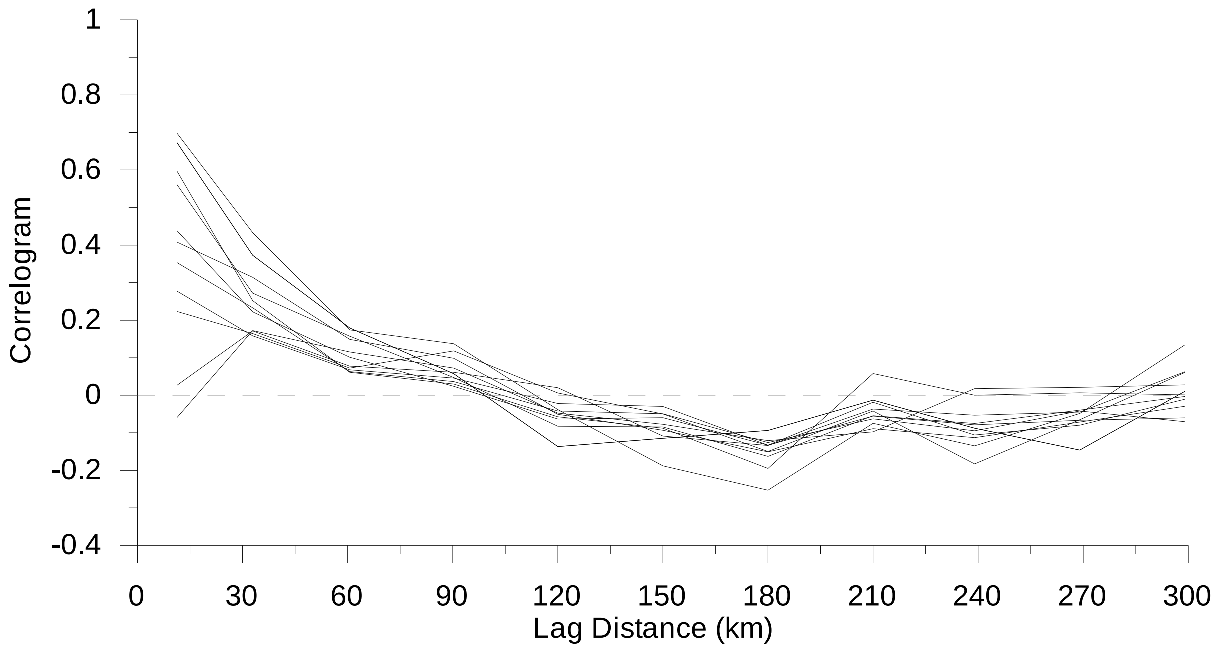


Figure 13 Monthly Correlogram based on multi-variables detrended monthly precipitation normals for Central region

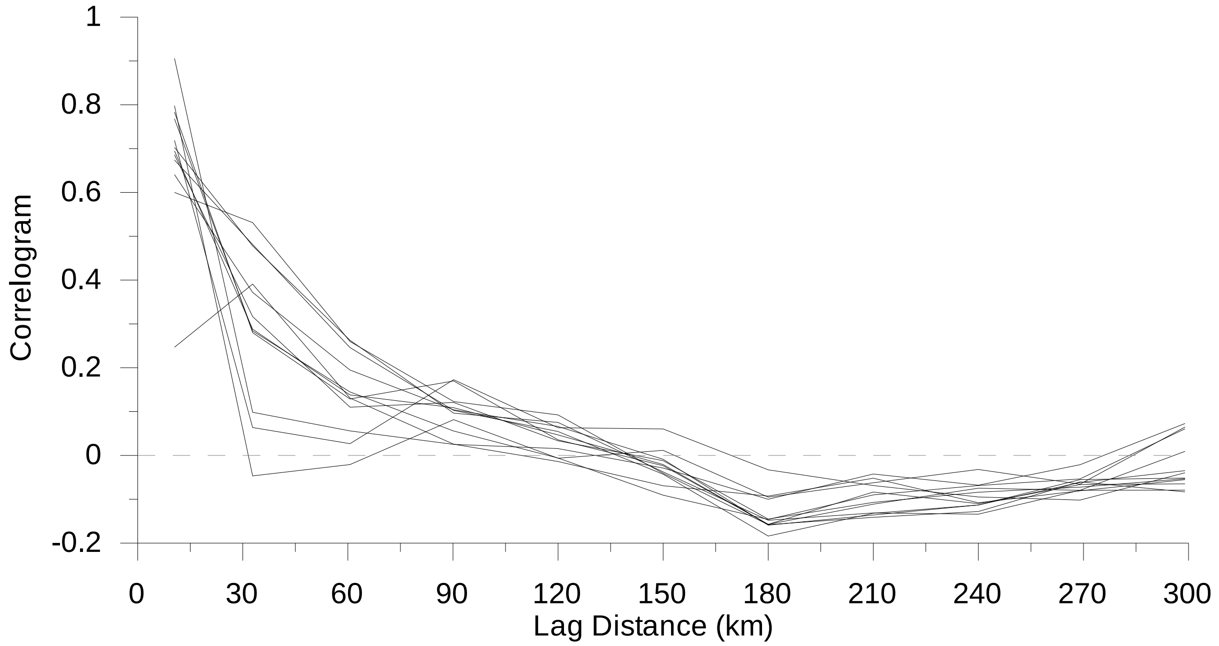


Figure 14 Monthly Correlogram based on multi-variables detrended monthly precipitation normals for Northern region

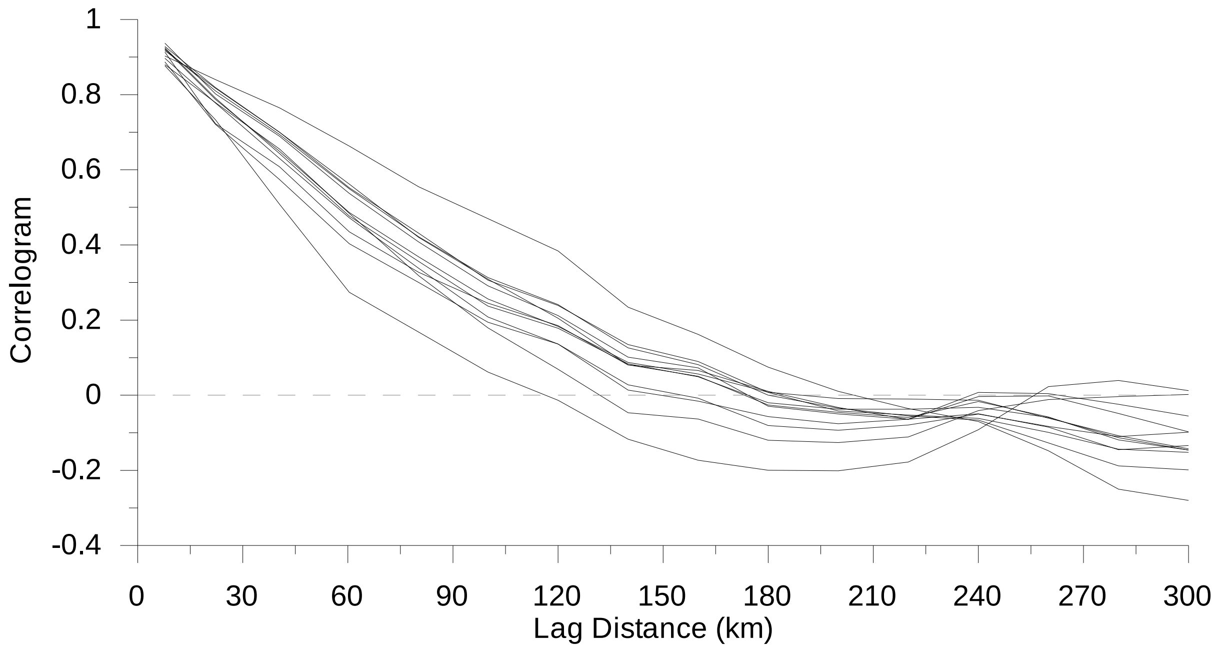


Figure 15 Monthly Correlogram based on original monthly precipitation normals for southern region

In this study, the distance is found around 120 km both for original and detrended residuals as shown from Figure 12 to Figure 17, so 120 km is used as searching distance in cross-validation and finally interpolation. In each following figure, each line represents one calendar month separately.

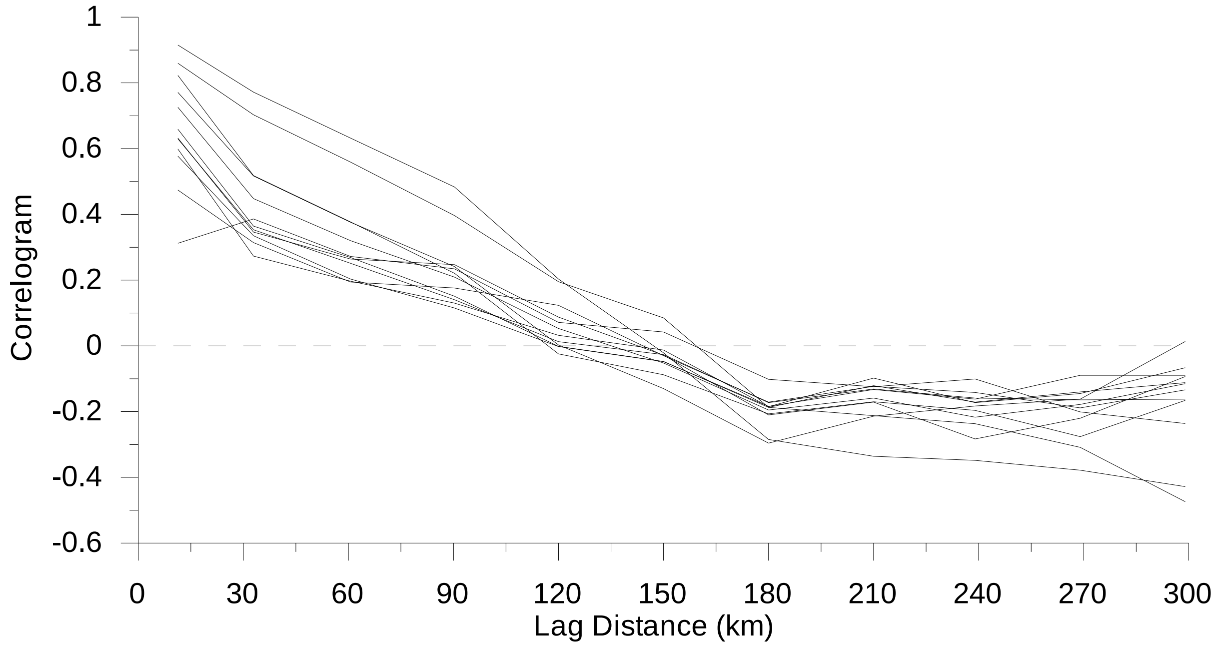


Figure 16 Monthly Correlogram based on original monthly precipitation normals for Central region

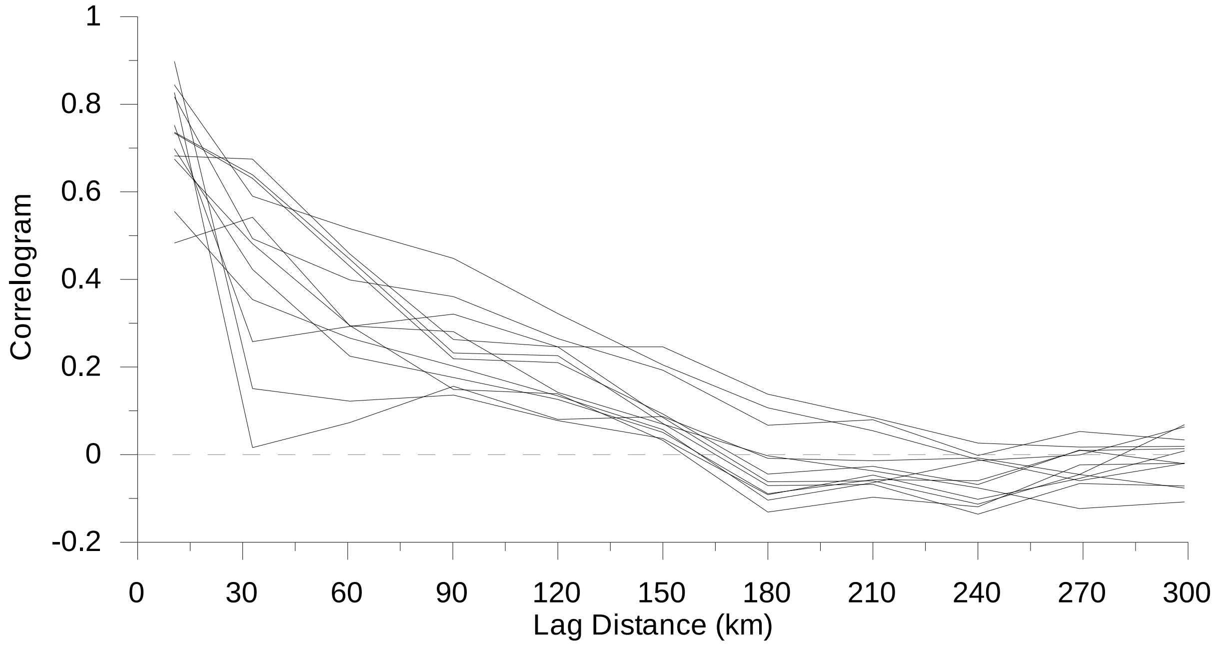


Figure 17 Monthly Correlogram based on original monthly precipitation normals for Northern region

5.2.2 Cross-Validation result for gridding monthly precipitation normals from 1971 to 2000

Utilizing the Geostatistical Analyst tool in ArcGIS, cross-validation is computed for each method in three regions. Then, statistical parameters for each method are computed and the comparison results are shown in Figure18 to 26 for Northern, Central and Southern region separately.

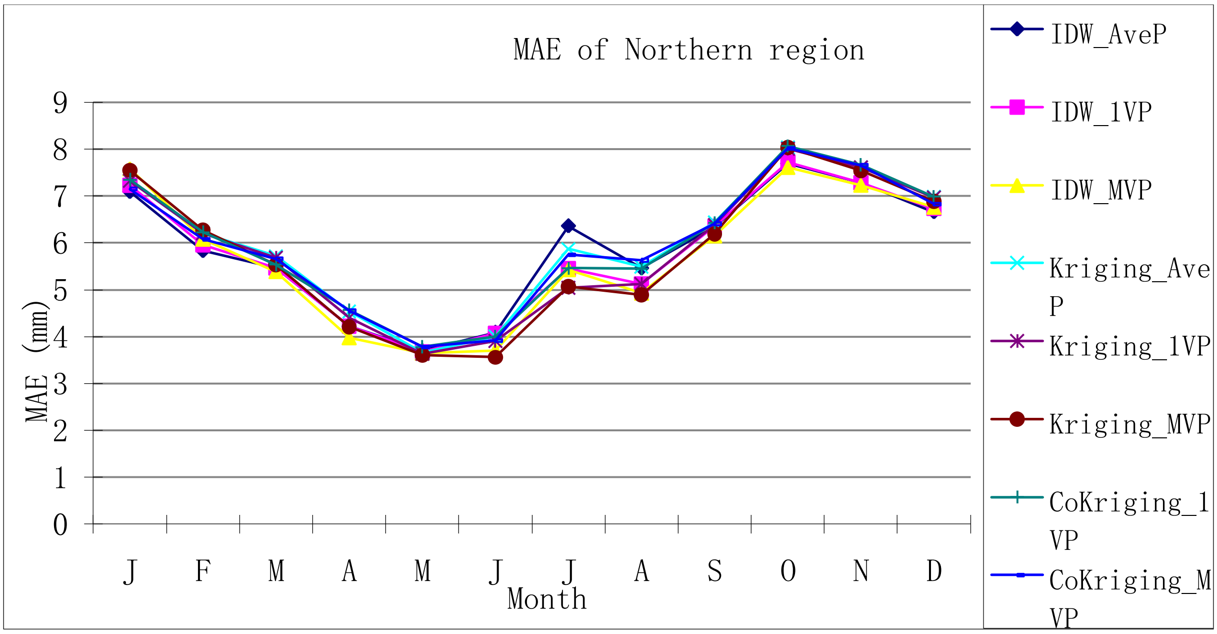


Figure18 Mean Absolute Error for different interpolation methods for North region

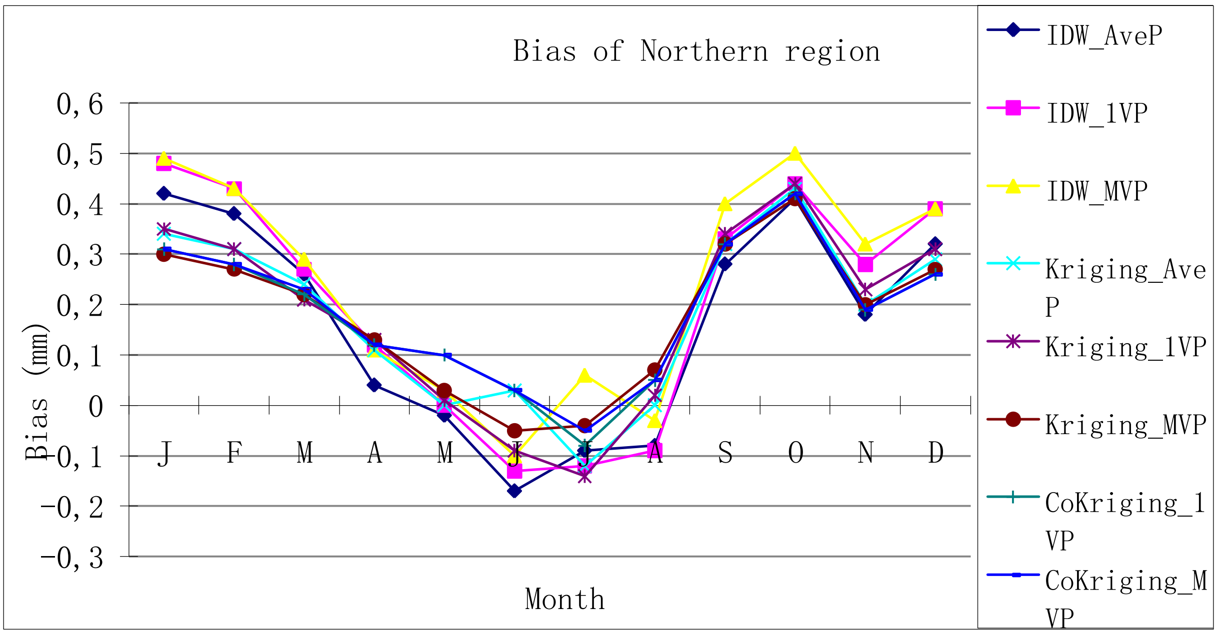


Figure 19 Bias for different interpolation methods for North region

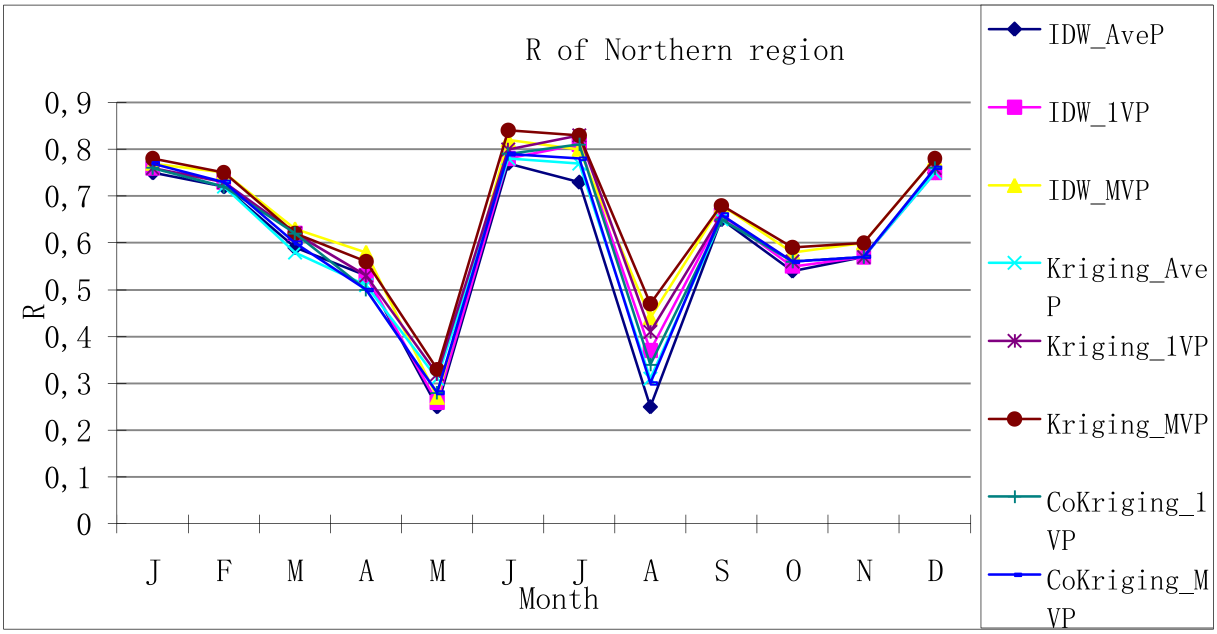


Figure 20 Correlation coefficient for different interpolation methods for Northern region

In Northern region of Sweden, different interpolation methods show similar pattern in mean absolute error, that decreases from winter to summer and increase from autumn to winter. Kriging with multiple variables shows the lowest error in summer time as shown in Figure 18. Inverse distance weighted method shows the lowest error in winter and part of spring. In Figure 19, the bias shows that all the methods overestimate the precipitation except in summer, which may be caused by the high mountainous area of Northern Sweden, and lower density of gauge stations. Figure 20 shows the correlation between the estimated precipitation data and observations. All methods show similar patterns while kriging with multiple methods show slightly better correlation in most part of the year.

In central part of Sweden, different interpolation methods show similar patterns in mean absolute error (Figure 21). Both kriging with multiple variables method and Inverse distance weighted with multiple variables method show lowest error. As shown in Figure 22, bias shows that all the methods will overestimate the precipitation except summer time, which may be also caused by the influence of topographical factors. Figure 23 shows different relations between estimated precipitation data and observations, all the methods show similar pattern while kriging with multiple method shows best correlation in most of the year. Cokriging with multiple variables method also shows high relation in winter and spring time, but lower relation during summer time.

In Southern Sweden, mean absolute error also gives similar patterns for each interpolation method as in Northern region, while kriging with multiple variables method shows lowest error as shown in Figure 24. The Bias for the Southern region shows that almost all the methods will underestimate normal precipitation, while krging with multiple variables method gives lower bias. Again, kriging with multiple variables method shows best correlation in southern region.

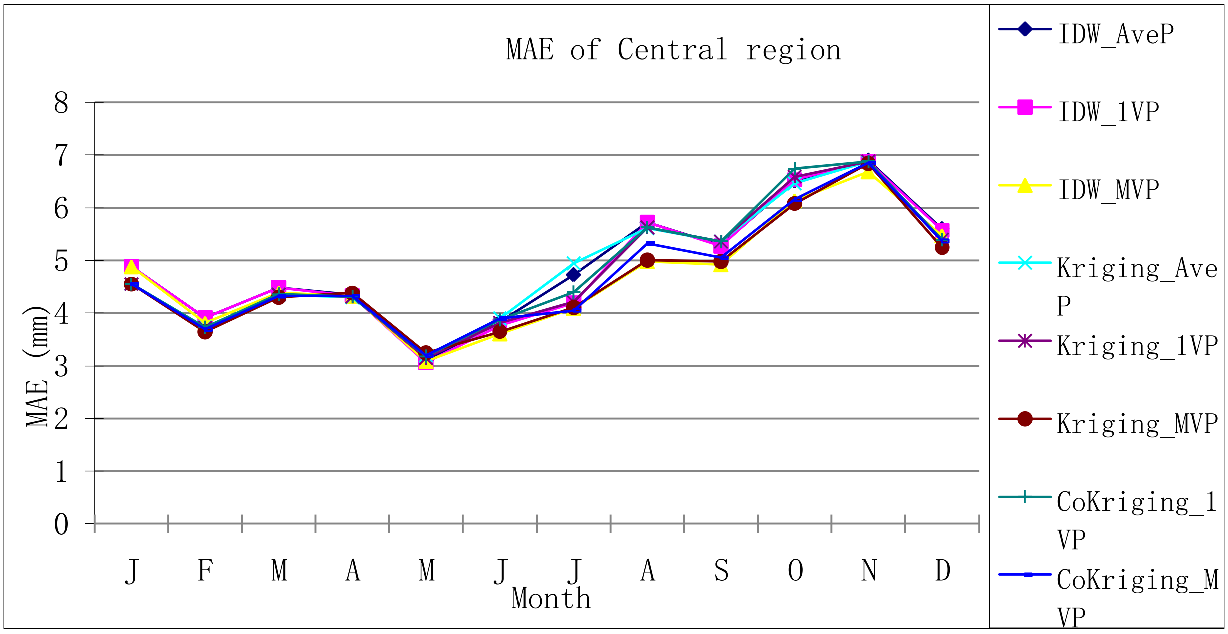


Figure 21 Mean Absolute Error for different interpolation methods for Central region

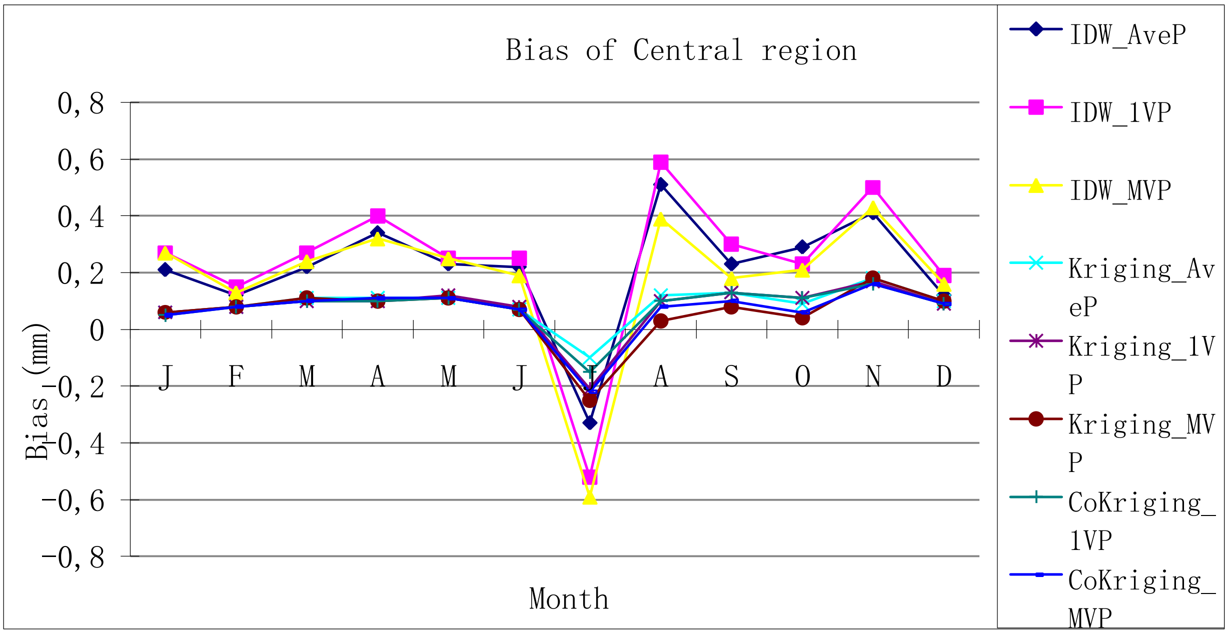


Figure 22 Bias for different interpolation methods for Central region

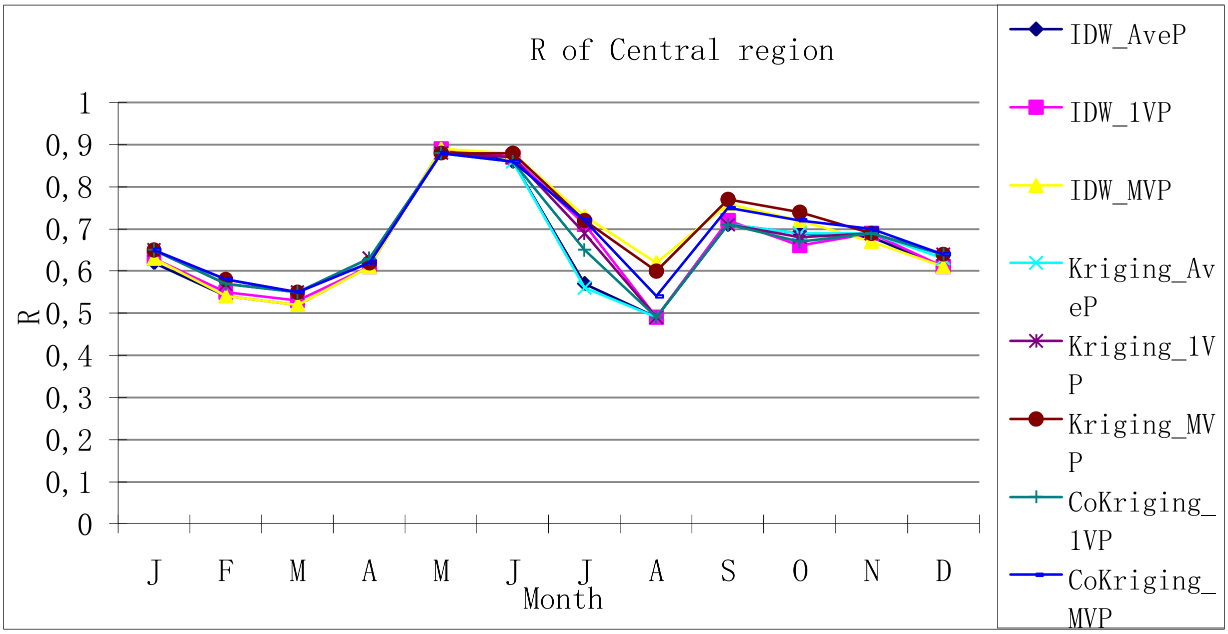


Figure 23 Correlation coefficient for different interpolation methods for Central region

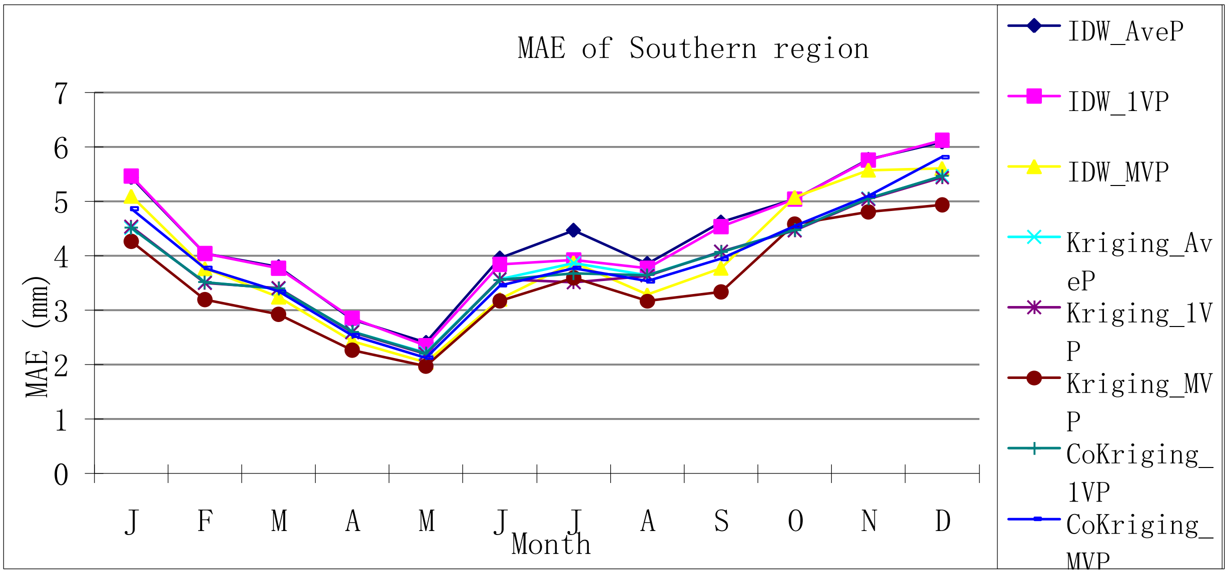


Figure 24 Mean Absolute Error for different interpolation methods for Southern region

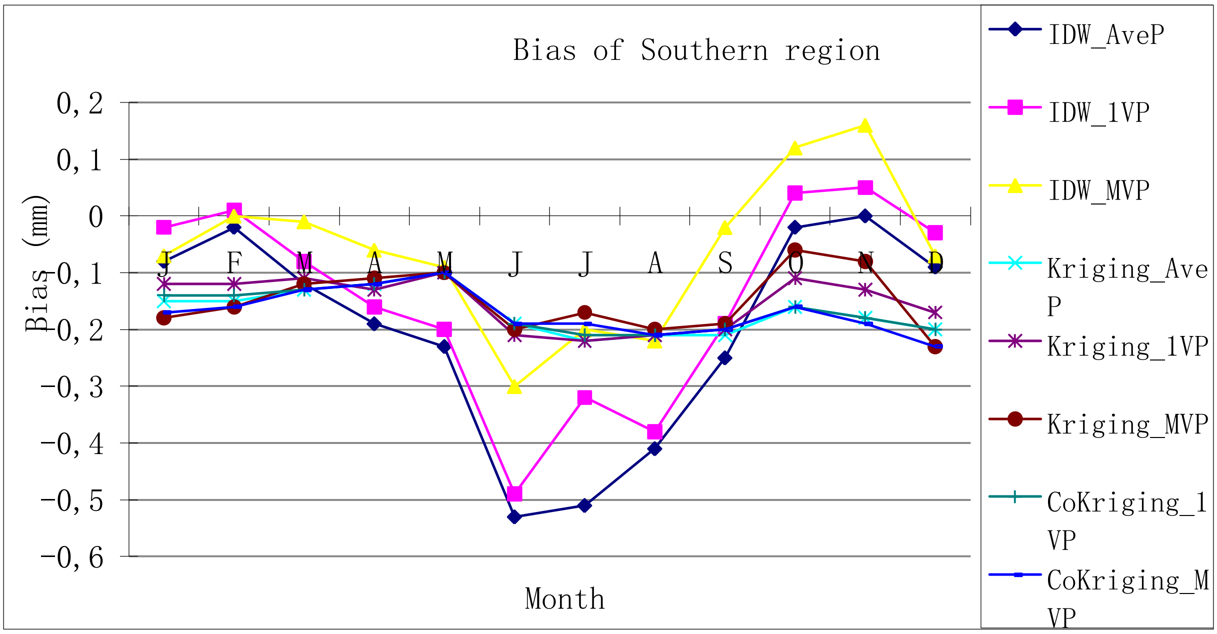


Figure 25.Bias for different interpolation methods for Southern region

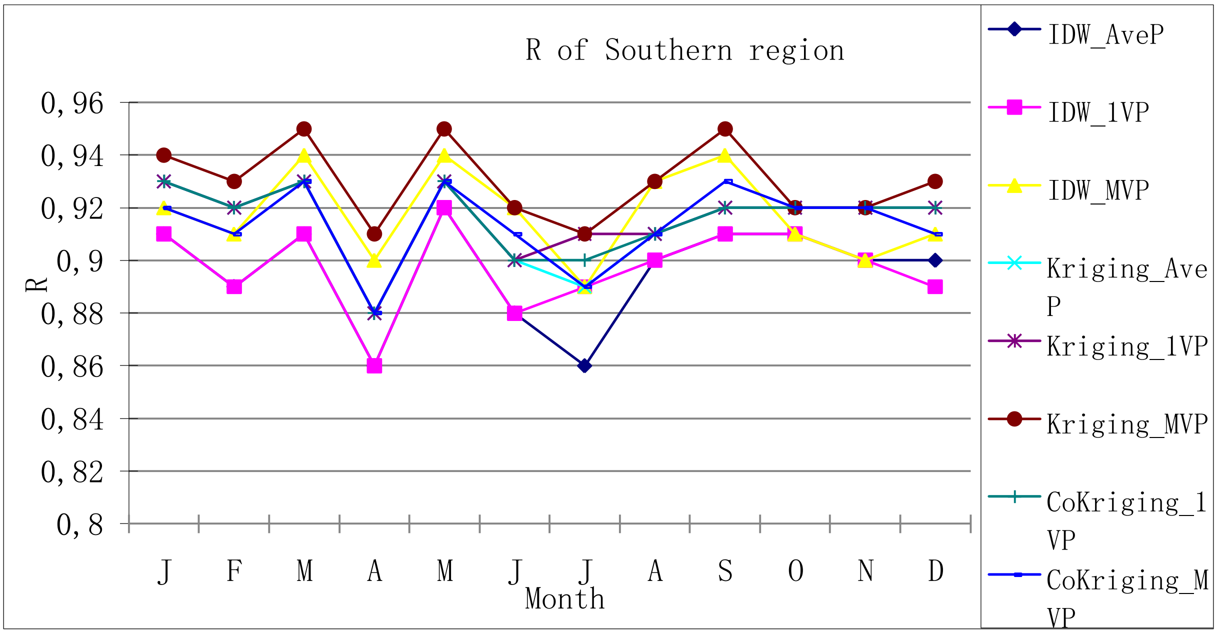


Figure 26.Correlation coefficient for different interpolation methods for Southern region

From Figure 18 to Figure 26, one result that can be found is that the detrending can increase the precision of kriging method very well, and can increase the prediction precision for IDW method in most cases, but will increase the bias sometimes. Using multiple variables will also increase the precision of the predictions for both kriging and IDW methods, however, it will decrease the precision by using cokriging method in most cases.

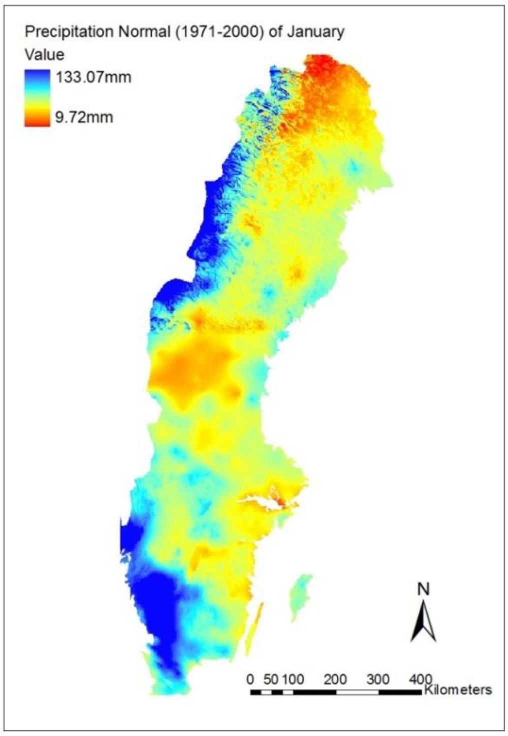
Comparing statistical errors, kriging with multi-variables shows lowest error in southern region, in the Central region during winter and in the Northern region during summer. From

the correlation coefficient figures, kriging with multi-variables method shows best relation in both southern and northern region, and in the Central region in autumn and winter. Other methods shows best results in some months, however, these methods do not perform equally well as kriging with multiple variables in each district.
Therefore, based on the result here kriging with multiple variables is the method chosen to interpolate the precipitation residuals here. Even though other methods also perform satisfyingly, using only one method keeps the consistency in choice of method.

5.3 Interpolating monthly precipitation normals for the period 1971 to 2000

Based on the cross-validation results for monthly precipitation normals data, the original normal precipitation were detrended by multiple variables and the residuals for each calendar month were interpolated with kriging method. Since the elevation and slope information at 2 km have been used in detrending, the residuals were also interpolated into 2 km spatial scale. To obtain the interpolated normal precipitation for each month, the trend that was removed prior to the interpolation of the residuals needs to be added to the interpolation result. Then, the results for each of the three regions need to be combined for each month. In order to decrease the influence of region division and to keep the spatial continuity of precipitation, an overlap distance of 10 km was chosen here at the borders of each region. This means that the Northern, the Central and the Southern region are extended by 5 km towards the neighboring region. Finally, the monthly precipitation normals were achieved and the result can be seen from Figure 27 to 38.

From these figures we can see that precipitation in the west region is generally higher than in east region of Sweden all around the year. The south-western region of Sweden and the lee side of Scandes receive higher amount of precipitation except in July. The east coast of Sweden usually receive less precipitation than the west coast except April, August, and November, when both east and west receive similar amount of precipitation. Around the year, the minimum amount of precipitation occurs in April and May, while the maximum occur in July. When comparing Southern and Northern regions, April and May receive more precipitation in the Southern region, while July receive more in the Northern region.



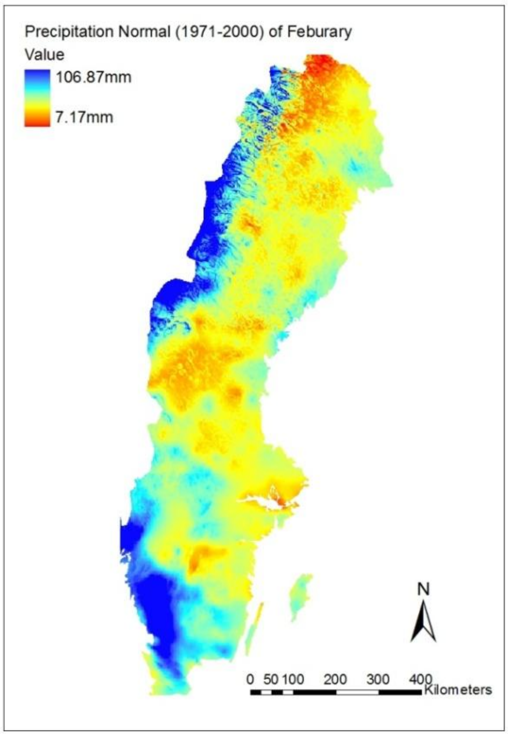
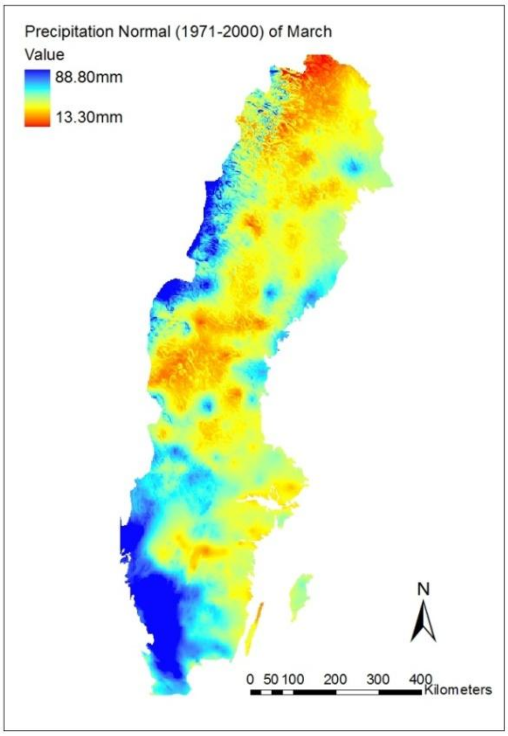


Figure 27: Interpolated precipitation normals for January for the period 1971 to 2000. The map shows an average for all January months within this period.

Figure 28: Same as Fig 27 but for February.



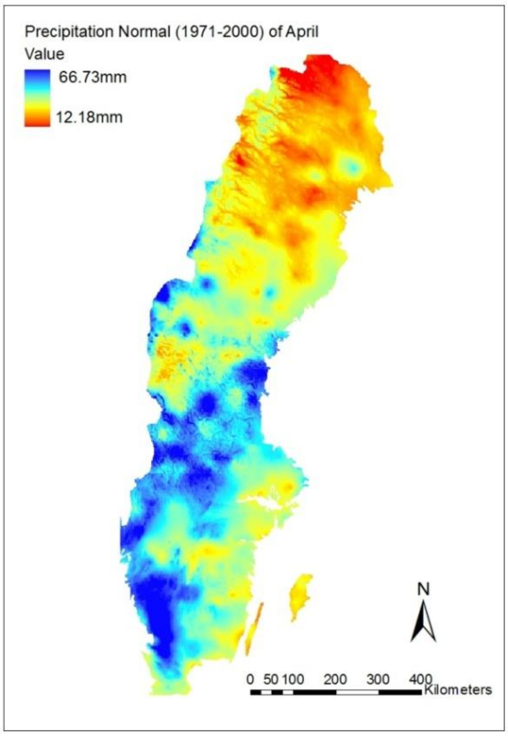


Figure 29: Same as Fig 27 but for March.

Figure 30: Same as Fig 27 but for April

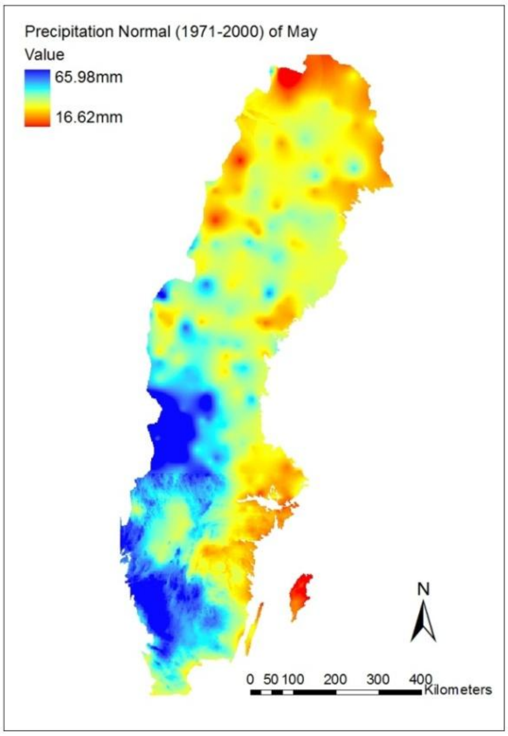


Figure 31: Same as Fig 27 but for May.

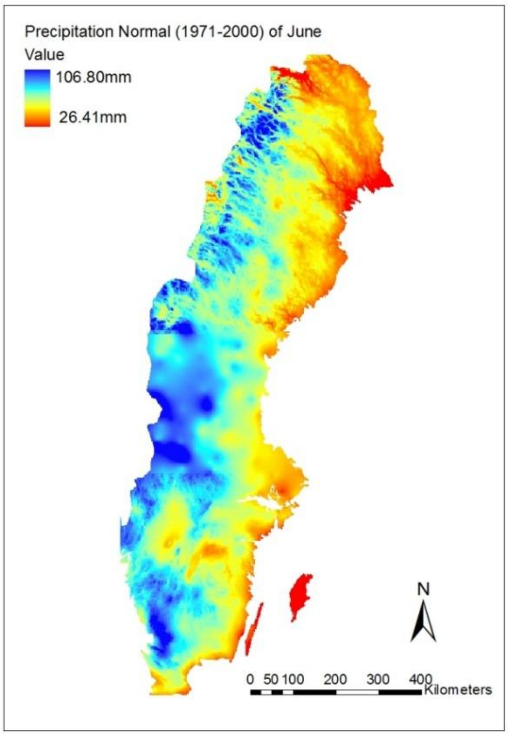


Figure 32: Same as Fig 27 but for June

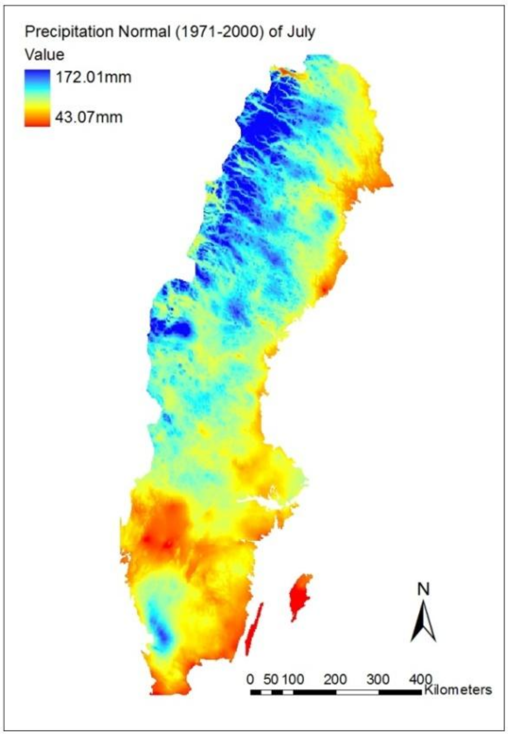


Figure 33: Same as Fig 27 but for July.

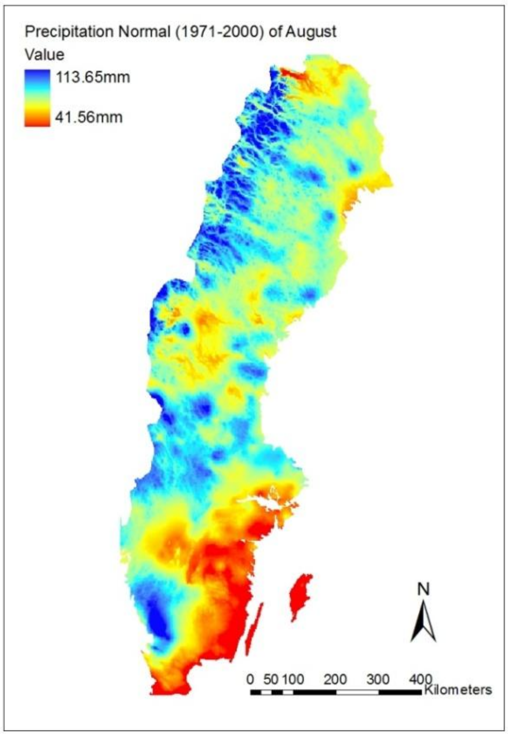
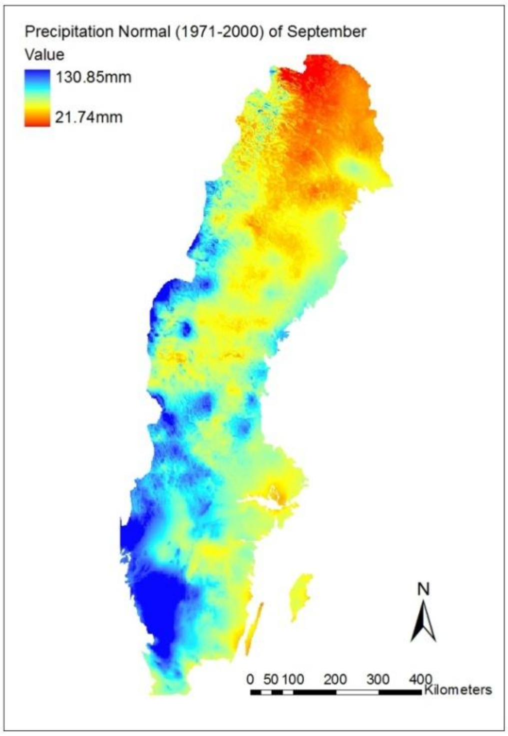


Figure 34: Same as Fig 27 but for August



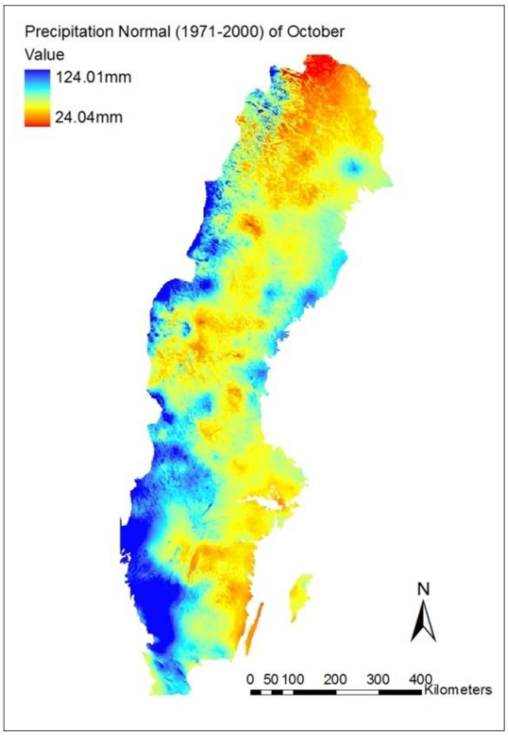
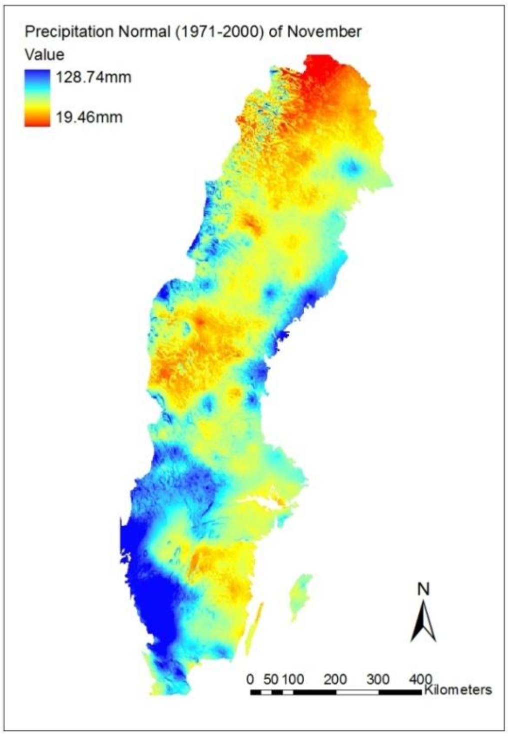


Figure 35: Same as Fig 27 but for September.

Figure 36: Same as Fig 27 but for October.



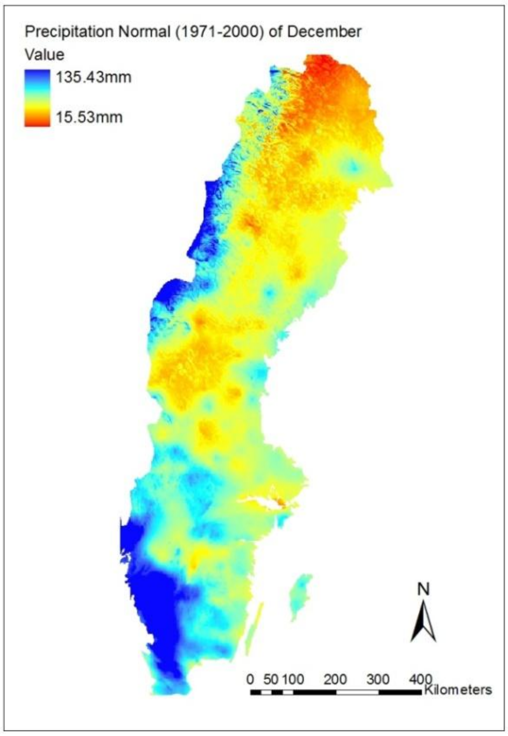


Figure 37: Same as Fig 27 but for November.

Figure 38: Same as Fig 27 but for December.

5.4 Interpolating monthly precipitation for the period 1961 to 2004

After receiving the precipitation normals distribution from 1971 to 2000, the dataset will be used in gridding monthly precipitation for period 1961 to 2004. This is done using kriging with detrended residuals. Since this method performs best for interpolating precipitation normals, it is assumed that it also will be the best choice for interpolating monthly precipitation.

In this section, the results in interpolating monthly precipitation for the period 1961 to 2004 will be described.

5.4.1 Monthly average variograms for the residuals

After deciding the number of stations to be used, precipitation normals based on the period 1971-2000 was subtracted from monthly precipitation to get monthly precipitation anomalies for the years 1961 to 2004. The average variograms are based on the monthly precipitation residuals. In the following table 4 to 6, parameters for monthly variograms for each region can be found. The variograms model used here is Exponential and all the nugget effect has been assumed to be zero to minimize the error caused by the data. The maximum lag distance is 280 km for Southern and Central region, and 350 km for the Northern region. The number of lags used is 15 for Southern region, 10 for the Central region, and 11 for the Northern region. The difference among the maximum lag distance and the number of lags in the three regions is caused by the difference in station density and number of stations.

When computing the average variograms, variograms for all the 44 calendar months have been computed first, and the average over all of them was taken as the final variogram result. One point that should be noted here is that there are some odd months in the 44 months that result in very different variograms compared to the majority of varigorams within one calendar month. As a consequence this may cause the average variogram to change considerably.

Table 4 Variogram parameters for Northern region based on monthly residuals

North	J	F	M	A	M	J	J	A	S	O	N	D
Sill (mm^2)	501	319	297	119	235	437	920	783	475	419	455	501
Range (km)	326	326	340	340	340	323	316	340	340	340	340	340

Table 5 Variogram parameters for Central region based on monthly residuals

Center	J	F	M	A	M	J	J	A	S	O	N	D
Sill (mm^2)	500	207	247	373	479	642	928	1042	708	723	598	1150
Range (km)	471	245	227	221	192	123	114	148	181	217	288	702

Table 6 Variogram parameters for Southern region based on monthly residuals

South	J	F	M	A	M	J	J	A	S	O	N	D
Sill (mm^2)	438	306	214	286	388	559	885	696	614	779	529	507
Range (km)	162	142	137	193	160	116	102	92	127	203	162	161

5.4.2 Interpolating monthly precipitation residuals from 1961 to 2004

Based on the monthly precipitation station data with missing data less than 5 years from 1961 to 2004, monthly precipitation anomalies for Sweden from 1961 to 2004 have been interpolated using kriging. Then, the interpolated monthly precipitation normals (1971-2000) has been added back to get the monthly precipitation. All the computation has been done in ArcGIS and the result has been saved both in Raster format and NetCDF format.

5.4.3 Inter-comparison of IDW, Kriging and Cokriging

Based on the result from the cross-validation procedure, kriging has shown to give the most realistic predictions when interpolating monthly precipitation normals from 1971 to 2000. Therefore, it is assumed that it also will be the best choice for interpolating monthly precipitation.

Despite this, even IDW and cokriging are applied to interpolate the monthly anomalies here. This is done to get an idea about how the choice of interpolation method affects the result and to estimate how well these methods perform for this task. Since single variable for cokriging showed better precision in estimating precipitation normals, only one variable - elevation is chosen for interpolating monthly precipitation. In this inter-comparison, kriging is the reference method against which IDW and cokriging are evaluated.

For each prediction point, the Correlation coefficient, Bias, and Root Mean Square Error have been computed between interpolated results of kriging, IDW and cokriging. The results are shown in Figure 39 to 44.

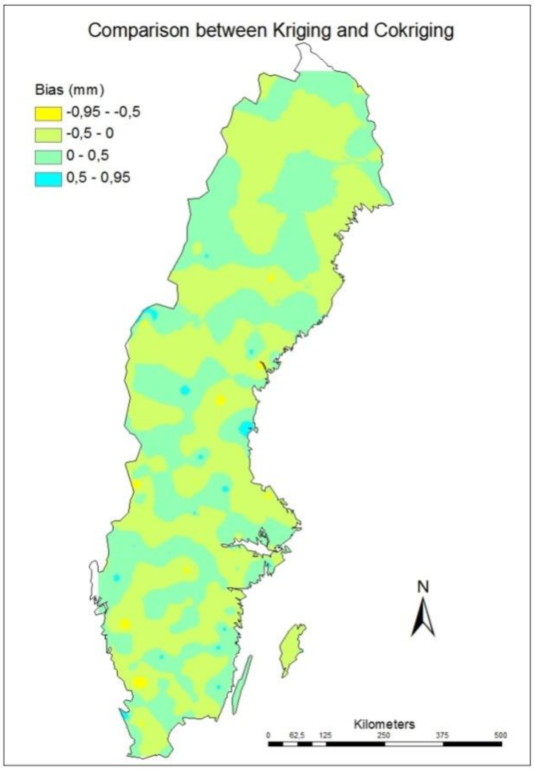


Figure 39 Bias comparing: Cokriging and Kriging

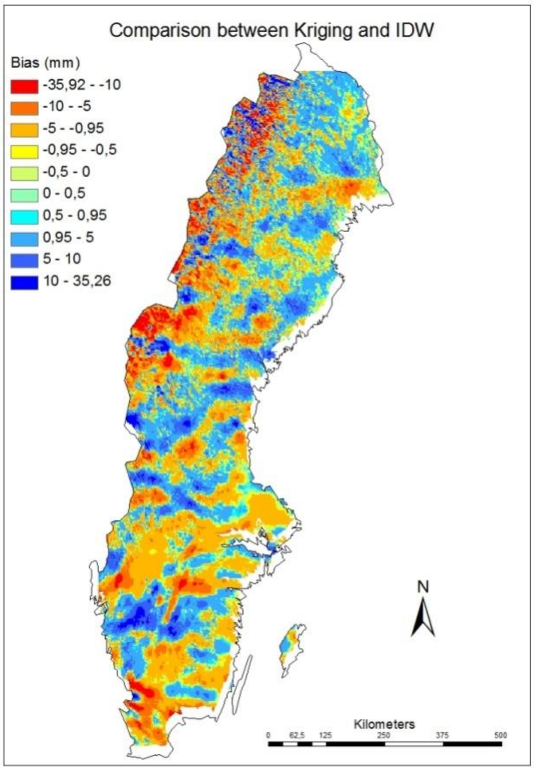


Figure 40 Bias comparing: IDW and Kriging

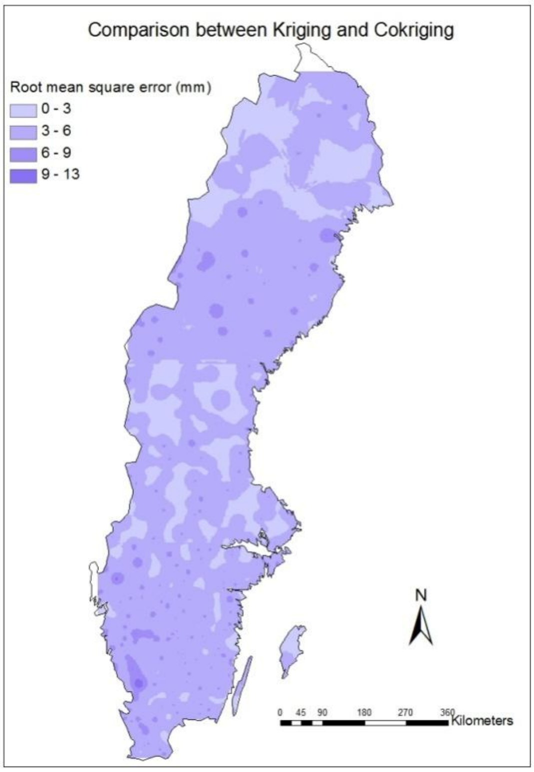


Figure 41 RMSE comparing: Cokriging and Kriging

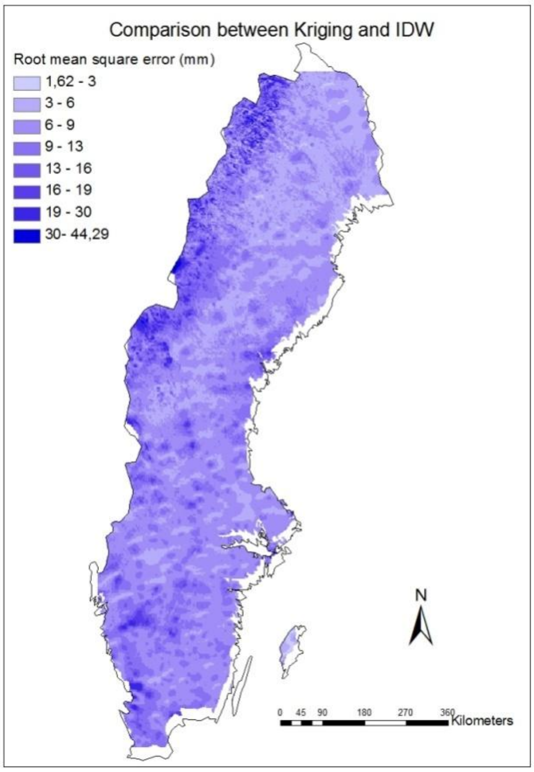
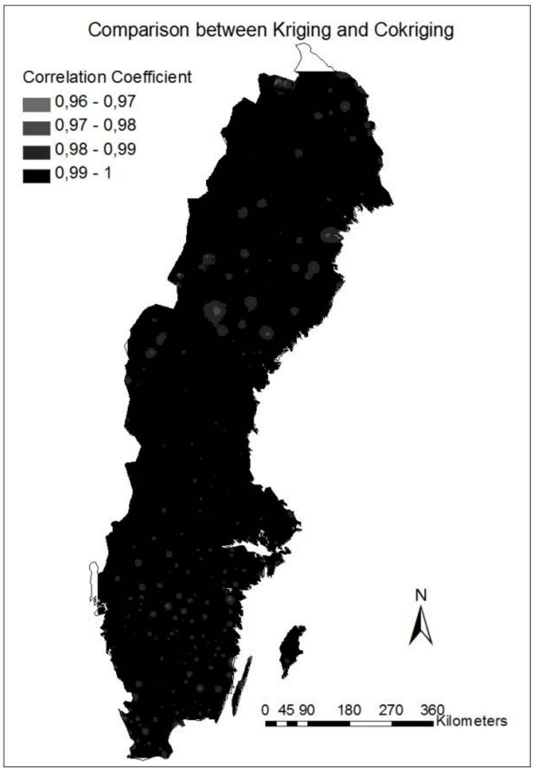


Figure 42 RMSE comparing: IDW and Kriging



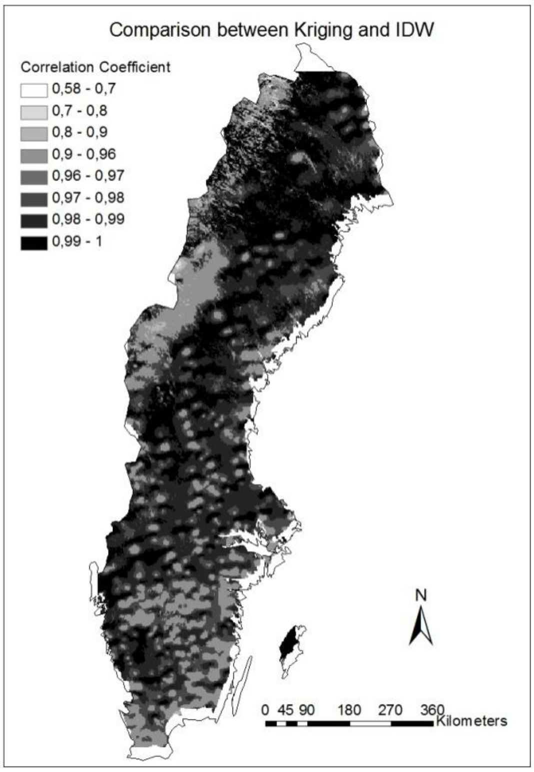


Figure 43 R comparing: Cokriging and Kriging

Figure 44 R comparing: IDW and Kriging

From the figures we can see, that the prediction results based on kriging and cokriging are very similar as indicated the correlation coefficient that is higher than 0.95, the bias that ranges between (-1,1), and the Root Mean Square Error that lies between 0 to 13 mm. Conversely, the difference between kriging and IDW is larger, especially in the northeastern region of Sweden. The Bias is between -35.92 to 35.26mm, which is much higher compared to cokriging. RMSE and R also showed large difference comparing with using cokriging method.

5.4.4 Validation with independent original station data

The previous validation using cross-validation was done for the interpolated precipitation normals for the period 1971-2000. Now the final interpolation result, i.e., gridded monthly means for the period 1961 to 2004 needs to be compared against observations in order to evaluate the final result. Since such an evaluation should be done on an independent data set, i.e., stations that have not previously been used in building the regression models to detrend the data, 133 unused original stations data have been chosen for this task. One point that should be noted here is that the time period for which the independent validation can be done has considerable gaps in the data series. There is data covering the period 1961 to 2004 but with a large amount of data missing. This is the reason why these 133 stations have not been included previously in the interpolation procedure (in all 5 to 10 years are missing between 1971 and 2000).

For each station, R, Bias, and MAE have been computed from the available observations and corresponding gridded value for all months in period 1961 to 2004. This is a continuous temporal comparison where those periods when observations are unavailable have been skipped. The result can be seen from Figure 45 to 47. From the maps we can see, that the agreement between interpolated and observed precipitation is generally lower in the mountainous area where stations density is rather low. The map for the Bias (Figure 46) shows that the interpolation often overestimates observed precipitation in the mountains which could be caused by including topographic factors in this study. The agreement between original precipitation and interpolation is generally higher in the southern and northeastern region of Sweden.

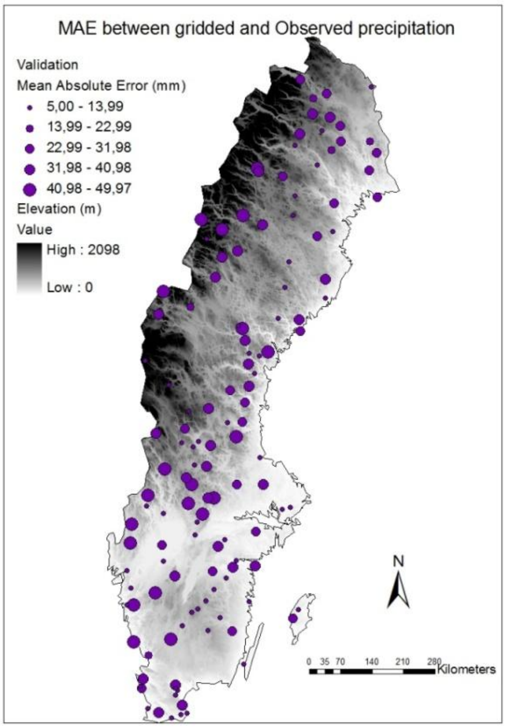


Figure 45 Mean absolute error of gridded monthly precipitation comparing with 133 unused stations.

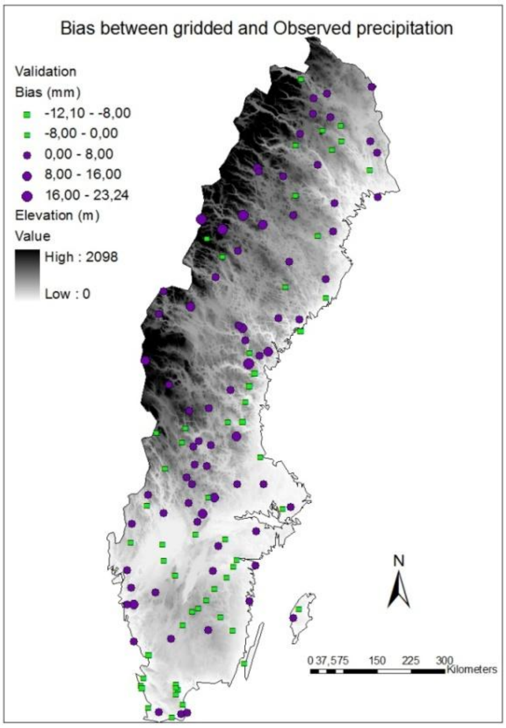


Figure 46 Bias of gridded monthly precipitation comparing with 133 unused stations.

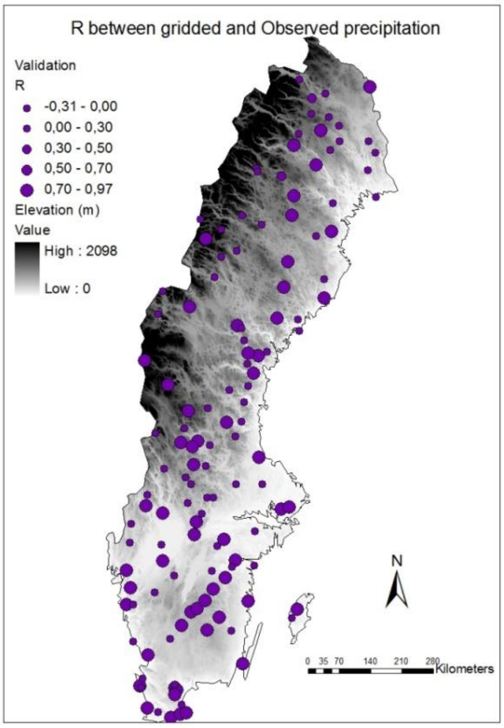


Figure 47 Correlation Coefficient between 133 unused stations and gridded results

6. Discussion

The aim of this study was to derive a gridded dataset of monthly precipitation through 1961 to 2004. To fulfill this task, two questions have been dealt with in detail. One considers the influence of topography on the spatial distribution of monthly precipitation normals, and the other one is concerned with finding the most suitable interpolation method to interpolate monthly precipitation.

The relation between original normal precipitation (1971-2000) and topography variables showed that Swedish precipitation is strongly controlled by elevation in the Southern region, the lowest R value is 0.3 including every spatial scales. Comparing with other regions, the relation is obvious, throughout the whole year, whereas in the Central and Northern region it is clearest during summer time. The highest correlation coefficient is up to 0.71. Earlier studies by Johansson (2000) and Linderson (2003) showed similar results for Sweden. Using different spatial resolutions of the DEM did not result in considerable differences in the correlation, which means that the relation between precipitation and elevation is quite stable from large scale to small scale. With the increasing of elevation, precipitation also increases. During winter time in the Northern region, winter and spring in the Central region, the relation between precipitation and elevation is rather low, which could be caused by variable wind directions in this regions. Previous study has shown that the region on the lee side of the Scandes including northern Sweden is protected against moist western winds from the Atlantic, and precipitation in the shielded area is mainly related to southeasterly winds (Uvo, 2003). Differences in the dominant wind direction could be the cause of the low relation. A previous study by Johansson and Chen (2003) considered wind in combination with other topographical factors which highly affected daily precipitation. When checking the relation between single station precipitation and elevation, the relation varied considerably from station to station, which indicates the relation between precipitation and topography is not stable across the country. This could also contribute to the low relation between precipitation and elevation in winter time in the Northern and Central region. Comparing with elevation, the relationship between precipitation and slope was more dependent on the spatial resolution of the DEM. The spatial scale 2 km was highly related in both Southern and Central region, while a resolution of 1 km gave better results in the Northern region. This is caused by the more rugged topography in the Northern region, giving more local topographical effect. The results were in line with Johansson et al. (2003) who describes the influence of slope on precipitation. The influence of different spatial scales of slope was found in this study that has not been done before. With increasing distance to west coast, precipitation generally decreases. PX showed a similar pattern but was higher correlated with precipitation than distance to west coast. PY showed generally negative relation with precipitation, which means that the higher latitudes had less precipitation. Comparing with other variables, curvature showed very low and unstable relationship, and has been discarded before constructing models.

The influence of spatial scale of the topographical variables on the relation with monthly precipitation has not systematically been tested before. Therefore, topographical variables were derived from the DEM for a number of different spatial resolutions. The analysis shows that there is no single resolution that was absolutely highest related with normal precipitation. However, the 2 km resolution showed generally better relation when considering all three regions, and have been used in gridding both precipitation normals and monthly precipitation. This could indicate that Swedish precipitation distribution is more influenced by topography within 2 km spatial resolution.

The trend models for the precipitation normals (1971-2000) explain the distribution of precipitation from 26.0% to 74.0% in the Southern region, from 9.6% to 65.6% in the Central region, and from 14.4% to 57.8% in the Northern region. From these findings it is concluded that topography have a considerable influence on Swedish precipitation.

Cross-validation results showed that kriging based on the data that was detrended with respect to multiple topographical variables had a better performance than IDW and cokriging in interpolating monthly precipitation normals from 1971 to 2000. It could be concluded that kriging in combination with detrended data is a useful and reliable method to create a gridded precipitation climatology for Sweden. The conclusion can also be drawn that detrending with multiple variables will increase the precision of kriging and IDW. Cokriging with single variable performs better than cokriging with multiple variables, which may be caused by the interactions between multiple variables. The result is consistent with the choice of interpolation method by Tveito et al. (1997), however, a comparison of methods has not been done in their study. Johansson et al. (2003) showed that optimal interpolation performed better than IDW, however, optimal method was not included in this study.

Inter-comparing showed that kriging and cokriging were very similar in predicting monthly precipitation from 1961 to 2004, while the difference between kriging and IDW was larger. For the comparison of cokriging and kriging, the Root Mean Square Error ranged from 0 to

13mm, the bias ranged from -0.95 and 0.95mm, and correlation coefficient were generally higher than 0.96, with a large part up to 0.99. Comparing the interpolation results from kriging and cokriging with the results from IDW, it was shown that IDW have the lowest precision and the largest error probably caused by the mountainous topography.

Kriging with multiple variables can predict unknown points with quite high correlation in large parts of the Southern region, and north-eastern part of Sweden. Larger errors occur in northwest Sweden that could be caused by the lower station density and more complex topography. The precipitation distribution was generally overestimated in the mountainous area, which may be caused by the high altitude.

In conclusion, the Swedish precipitation distribution could be partially explained by topographical variables, and the kriging with detrended data could be used in the gridding procedure.

The results from these study point towards several questions that could be addressed in further studies. One is to more closely investigate the low relation between monthly precipitation normals and elevation in northern and central region in winter time. For example, the relation between winter precipitation in northern and central Sweden is quite low. To further study this finding, the most frequent wind direction could be check to explain the low correlation in the future, the mountainous area could also be separated from the northern and central region, and the relation between precipitation and topographical variables could be analyzed in more detail. Further, cross-validation could be done in the future to check the precision of the predictions by using kriging, or the influence of station density on the interpolation outcome could be studied.

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