Spatial Precipitation Modeling for the Tyrol Region

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Aim of the study was to create a precipitation map of Tyrol and adjacent zones by interpolating existing point data to a continuous surface. Rain gauge data was obtained from the responsible organizations. Among the 563 stations, only few were situated at high altitudes. For this reason, precipitation at the ELA of Austrian and Italian glaciers was calculated using the temperature-precipitation relationship introduced by *Ohmura et al.* (1998). The point data (station and glacier) were interpolated to a 1 x 1 km lattice. For this purpose, we developed the so called GRADGRID interpolation algorithm, which is connecting features of different older algorithms. Elevation is taken into account by regression. The calculated precipitation patterns were well corresponding to the results of existing comparable studies.

1. Introduction

Conventional precipitation data is collected by rain gauges and thus of a one-dimensional character. To get continuous maps, any type of spatial interpolation is necessary. In rather flat regions with little spatial variation of the precipitation and relatively even distribution of the gauges, relatively simple interpolations can provide reliable results. For Tyrol and adjacent zones of Bavaria, Northern Italy and Switzerland, which were object of this study, the reverse is the case. Precipitation in mountainous terrain is highly variable over short horizontal distances. Furthermore, the distribution of rain gauges is quite uneven and not representative because of a concentration in lower altitudes and only few stations in high-altitude places. For those reasons, it is a real challenge to try extrapolating the point values obtained from the rain gauges to the surface. Some authors have tried to compute grid-based precipitation climatologies of the Alps, the most recent ones *Frei & Schär* (1997) and *Schwarb* (2001). Both of them covered the whole Alps including the forelands, using a data set of more then 6000 stations. *Frei & Schär* drew a grid of 24 km spacing and interpolated the rain gauge values to grid point values by using the so called SYMAP-algorithm. For each grid point, all gauges within a distance of one mesh width were included in the calculation. If there were less than four stations in that circle, the distance was extended one more mesh width, and this process was repeated until at least four gauges were included. If the search radius was four times the mesh width and the stations were still less than four, a no data value was assigned to the grid point. Each gauge value was weighted according to its distance to the grid point and to the spatial clustering of gauges. The restriction of the SYMAP-algorithm is that it does not take into account the altitude.

Schwarb (2001) used the PRISM-algorithm, which was developed in the United States and applied for interpolating different phenomena. Schwarb drew a grid with 2,5 km spacing. The selection of rain gauges for the calculation of each grid point value was more complicated than in the case of *Frei & Schär*, because it was based on different parameters. The weighting of the rain gauge values also included multiple factors. But the main difference to the SYMAP-algorithm was that for each grid point all the gauge values selected for calculation were plotted in a diagram versus the altitude. A regression line was computed, and the value for the grid point was assigned based on the regression line and the altitude of the grid point. On this way, the altitude was taken into account, indicating that the method is more applicable for mountainous terrain. The general patterns of the results of *Frei & Schär* and of *Schwarb* were quite similar. But in addition to the higher resolution, the map of Schwarb shows higher precipitation in high altitudes compared with the map of *Frei & Schär*.

Neither of the authors tried to obtain additional data from high elevations, so that the results were only based on the few high-altitude gauges, on adjacent low-altitude stations and in the case of *Schwarb* on the extrapolation with gradients obtained from linear regression.

2. Methods

2.1. Precipitation data from rain gauges

Precipitation data from 563 stations was collected on a monthly base. The lengths of the series differ between a few years and more than thirty years. 30-year averages from the period 1961 to 1990 were used for calculations, neglecting stations with less than 20 values.

For some areas at the edge of the research area, there was no data available for the required period. Data of adjacent zones with comparable climatic conditions were correlated with data from the period 1931 - 1960 compiled by *Fliri* (1975). Excellent regression results and variations between the dataset 1931 - 1960 and that 1961 - 1990 of usually less than 3 % allowed us to use the data from *Fliri* for the data-less zones without further processing. So gaps could be filled. For some critical zones, like parts of the lower Inn Valley, neither recent data nor data from *Fliri* was available. Because of the rather homogeneous climatic conditions in these areas, some supporting points were interpolated between the existing rain gauges.

All of the data was applied without any corrections of systematic errors or removal of uncertain values - such data processing would have been out of our scope.

2.2. High altitude data

1. Precipitation data from glaciers

For getting more precipitation-values in high altitude areas, we included data from glaciers, using a temperature-precipitation-relationship at the ELA presented by *Ohmura* et al. (1997). Annual precipitation is obtained like follows:

$$P_{a,\,OKF} = 645 + 296\ T_{s,\,OKF} + 9T_{s,\,OKF}^2, \quad \text{eq. (1)}$$

where $P_{a,\,OKF}$ is the computed annual precipitation at the ELA and $T_{s,\,OKF}$ is the average summer temperature (June to August) at the ELA, adapted to eq. (1). The relationship is based on glaciers from different climatic zones, so the parameters had to be corrected to be applicable for the Alps (see below).

The ELA of the glaciers was taken from the "Österreichische Gletscherkataster" (Austrian Glacier Cataster), obtained by the 2:1 accumulation area:ablation area relationship. The data set is based on research from 1969, when the glaciers were near equilibrium, so that eq. (1) is applicable.

Some ELAs from the Ortler Mountains and the Ötztaler Alpen were also available for Alto Adige (*Stötter* 1994).

Sets of adjacent small glaciers were unified by computing averages of ELA and coordinates, weighted by their glacier surface, to avoid an overrepresentation of glacier values (the Cataster provided data for more than 900 single glaciers).

Some ELAs were corrected downwards (Vent Region, 200 m) or upwards (Eiskar in the Carnian Alps, to 2600 m), they did not represent the climatic conditions because an account of local effects (exposition, slope, local precipitation patterns). One imaginary ELA of 2500 m was set in the Central Karwendel (near to the Birkkarspitze) due to data from a late Pleistocene glaciation.

To compute the summer temperature at the ELA of the glaciers, a data set of available high-altitude gauges was compiled. Using only gauges with series of 30 years (1961 - 1990), we plotted the average values for summer temperature versus the altitude and computed a linear regression function,

$$T_s = 0{,}0063 * A + 20{,}442, \qquad \text{eq. (2)}$$

where T_S is the average summer temperature and A stands for the altitude. With this equation and the ELA, temperatures could be calculated. To adapt them to the Ohmura-Temperatures, we had to convert the meteorological temperatures to temperatures fitting to the OKF-relationship,

$$T_{s,\,OKF} = T_s + 0{,}5, \qquad \text{eq. (3)}$$

an empirical equation where $T_{s,\,OKF}$ is summer temperature applicable for the OKF-relationship and T_s is the meteorological summer temperature. After applying eq. (3), the computed precipitation had to be converted to the meteorological precipitation,

$$P_a = 0{,}95 * P_{a,\,OKF} + 5, \qquad \text{eq. (4)}$$

an empirical relationship where P_a is the meteorological precipitation and $P_{a,\,OKF}$ the precipitation obtained from eq. (1).

2. Data calculated by vertical gradients

For some regions in the Central and Southern Alps (especially regions near Livigno and the Belluno Province), neither glacier data nor high altitude station data was available. We used adjacent valley stations and applicable vertical precipitation gradients to construct some virtual stations on mountaintops. The vertical gradients were obtained from *Sevruk* (1975) - we applied the gradient for the Trentino to the Belluno Province (23 mm per 100 m) and the gradient for Graubuenden to the Livigno area (44 mm per 100 m).

2.3. Elevational gradients

The estimation of vertical precipitation gradients was problematic for regions without glacier data. No applicable glacier datasets were available for Italy (except the Ortler Mountains) and adjacent Switzerland. Also from the Northern Alps, only few glacier data was available because of lack of glaciers. For those regions, altitudinal gradients had to be specified. *Sevruk* (1975) has calculated such gradients for different climatic regions of Switzerland. They are difficult to apply for the whole research area, because gradients there show a different pattern according to the PRISM-algorithm (*Schwarb* 2001). We calculated some local gradients from valley stations and adjacent high elevation stations respectively glaciers. However, due to their wide spacing it was not possible to interpolate them to the surface without huge uncertainties. Instead, we decided to take gradients into account by regression (see below).

2.4. The interpolation algorithm GRADGRID

With the system of rain gauge precipitation values, inter- and extrapolated data and computed precipitation on the ELA of glaciers, the net was dense enough for an interpolation to a lattice. We set a spacing of 1 km and created an interpolation model connecting the simplicity of SYMAP and the altitudinal regression of PRISM. We developed the algorithm with the software Visual Basic for Applications and called it GRADGRID. It is operating in three steps, considering the grid point as basic entity. The steps are repeated for each grid point. Operation time was about twenty minutes (for about 50.000 lattice points).

Step 1:

The selection of data for the lattice point is based on the same principle as in SYMAP. The basic search radius was set to one mesh width (1 km). During the calculation, the program can extend the search radius several times (a maximum of 19 times was set) with steps of one basic search radius each (thus, to a maximum of 20 km), until at least a minimum number (in our case four) of data points - station or glacier - are located within the search radius. If fewer than the minimum number of data points are located within the maximum search radius, the no data value is assigned to the grid point.

Compared with the SYMAP-algorithm, weighting of the data points was simplified and is only a function of distance between the value and the grid point,

$$P_w = P_o * e^{-d/s}, \qquad \text{eq. (5)}$$

where P_w is the weighted precipitation of a station, P_o is the original precipitation, d is the distance between data point and grid point and s is the basic search radius. The procedure is repeated for each station within the search radius.

Weighted averages of the precipitation values and the altitudes are calculated for the grid point.

Step 2:

A second query is performed to select data points to be included in the calculation of the vertical precipitation gradient being applied to the lattice point. Additionally to a minimum number of stations, a minimum difference in altitude between the highest and the lowest included station is required. This is to ensure that the gradient will not be determined only by horizontal effects and statistical uncertainties among stations on similar elevations. The search radius could be too large in regions with little high altitude data - in such cases, horizontal gradients and spatial uncertainties can have negative impacts on the accuracy of the result. The maximum search radius was set to 60 km. The minimum altitude difference was set to 1000 meters, the minimum search radius to 2 km and the minimum number of stations remained the same as in step 1.

The included stations are weighted like in eq. (5), with the difference that s is not the basic search radius but the real search radius. This is to avoid too much down weighting of stations farther away which would be detrimental to the calculation of proper gradients.

The precipitation values are plotted versus the altitude and a weighted linear regression is computed based on minimizing the square error. The inclination of the regression function is representing the vertical precipitation gradient.

Step 3:

Grid point precipitation is calculated from the results of step 1 and step 2, based on the altitude of the grid point,

$$P_G = P_A + k_R * (z_G - z_A), \qquad \text{eq. (6)}$$

where P_G is the grid point precipitation, P_A is the crude grid point precipitation of step 1, k_R is the inclination of the regression line, z_G is the altitude of the grid point (obtained from a digital elevation model) and z_A is the average station altitude for the grid point.

2.5. Calculations

The following calculations were carried out:

A. annual precipitation: based on 30-year averages from the period 1961 to 1990, including glacier data

B. seasonal precipitation: 30-year averages from 1961 to 1990, excluding glacier data (no seasonal values available). Spring = March to May, summer = June to August, autumn = September to November, winter = December to February. First the percentage of the precipitation of each season of the annual sum was calculated for each station. The percentages were interpolated with GRADGRID, but without using the precipitation-altitude-regression. The percentage values of each grid point were then multiplied with the annual precipitation for the same grid point obtained in calculation A. Because of the fact that vertical precipitation gradients show quite stable patterns all over the year (*Schwarb* 2001) and that the variations of low elevation stations can be applied to adjacent high elevation zones without significant error, that method, despite its simplicity, should not lead to an oversimplification or a distortion of the results.

3. Results and discussion

3.1. Annual precipitation

The application of GRIDGRAD on the station and glacier data showed pronounced variations along a transect across the Alps. The outputs are well corresponding to the results of *Fliri* (1975) and *Schwarb* (2001). They are difficult to compare with the results of *Frei & Schär* (1998) because of their much higher spatial resolution.

Along the northern rim of the Alps, a positive precipitation anomaly could clearly be detected. The Bregenzerwald Mountains, the Karwendel and Rofan

Mountains and the Chiemsee Mountains were particularly moist with annual sums of up to more than 2000 mm. The same was true for the Southern rim, even although only the south-easternmost edge of the research area touched this region. The rain-shaded Inner Alps were comparatively dry, which was especially valid for the Venosta Valley with annual sums of slightly above 500 mm. But also the other valleys of Alto Adige and the upper Inn Valley received less than 800 mm. In the massifs of the Central Alps, precipitation was intermediate, only the northern slope of the Hohe Tauern and the Zillertal Mountains received more than 1500 mm precipitation over significant parts of their ranges.

3.2. Seasonal precipitation

A. spring precipitation

The spring percentage shows no clear patterns. In general, it is lower in the Central Alps and higher in the outer ranges and valleys and in the Northern foreland. A negative anomaly (lower than 17,5 %) is located in the Sesvenna Mountains, a positive one (approaching 30 % of the annual sum) in some parts of the Ortles Mountains.

Spring precipitation is highest in the Bregenzerwald Mountains, the Allgaeu Mountains, some more spots in the Northern Alps and the Carnian Alps in the southeast, the only regions with more than 500 mm. In contrast, some inner alpine valleys like Upper Inn valley, Engadina Bassa, Venosta valley and the Bressanone region receive more than 150 mm.

B. summer precipitation

The percentage of summer precipitation is much lower in the Southern Alps than in the Northern Alps. It is highest in the Dolomites and the Oetztaler Alpen (it surpassed 42,5 % in some regions), while farther East in the Central Alps it decreases. An obvious negative anomaly can be observed in the Texel Mountains north of Merano.

The higher share of winter precipitation in the Southern Alps can clearly be assigned to the mediterranean influence. However, a closer look to the conditions in the Central Alps is necessary. Where mediterranean low pressure cells can proceed as far north during winter and cause significant winter precipitation, the percentage is lower (very good to observe in the Texel Mountains, which can be approached by the air masses via the corridor of the Adige valley). Where such corridors are lacking, annual precipitation can largely be assigned to convective processes during summer.

In absolute means, summer precipitation is highest in the Northern and Central Alps (except the drier southern part of the Oetztal mountains) with maxima reaching beyond 800 mm. Inner alpine valleys are comparatively dry with values lower than 300 mm. The same is valid for the Southern Alps, except some high elevation spots like Ortles and Marmolada.

C. autumn precipitation

With the percentage, a clear North-South-gradient could be observed. While only 17,5 to 22,5 % of the annual precipitation occur during autumn in the North, in the Southern part of the research area the value rises up to more than 27,5 %, in the Carnian Alps even above 30 % - a general pattern which is clearly representing the submediterranean influence in the Southern Alps.

In absolute means, autumn precipitation is highest in the Carnian Alps, too, approaching 600 mm. Also in the Bregenzerwald Mountains and some further spots in the Northern Alps, 500 mm are surpassed. As in the other seasons, the inner alpine valleys - especially Venosta Valley - are dry with less than 150 mm precipitation.

D. winter precipitation

The percentage of winter precipitation is extraordinary low in some areas within the Southern Central Alps like the Venosta Valley, the Sarntal Mountains and parts of the Dolomites, not surpassing 12,5 % of the annual sum. In contrast, the highest percentages are reached in the Northwest of the research area, where 20 - 25 % of precipitation is provided during wintertime.

In absolute means, the pattern is very similar. Inner alpine regions often receive less than 100 mm autumn precipitation, while in the Northern Alps - especially the Bregenzerwald Mountains - 500 mm are surpassed in some places.

This pattern can be explained with lacking convectional precipitation during winter, being the major source of summer precipitation in the rain-shaded Central Alps, and the prevailing westerly winds with cyclones providing significant precipitation at the northern edge of the Alps.

4. Conclusions

In general, our results proved to be consistent with comparable studies and with the expected climatic characteristics of the research area. Additionally to the uncertainties of the measured precipitation at the gauges, the following problems could decrease the accuracy of the results:

In the regions without glacier data, the vertical precipitation gradients are based on the gradients from climatically comparable areas in Switzerland and the gradients obtained by automatic regression with extensive search radius (up to more than 50 kilometers).

The glacier data itself has to be considered as rough approximation. The factor of 0,95 was based on a subjective sample of data.

Therefore, the high altitude data has to be considered with attention. It should give an approximation to the real conditions, but the absolute figures can differ from the real ones. Due to the interpolation algorithm with different station samples it is difficult to quantify the expectable error and to assign confidence intervals to the grid cells.

The spatial resolution of the lattice (1 x 1 km) is actually much higher than the station density would allow, but due to the fact that the resulting maps should be presented to a broader public with a scale of about 1 : 600 000, cartographic requirements had to be taken into account.

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