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Geostatistical merging of rain gauge and radar data for high temporal resolutions and various station density scenarios

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SUMMARY

This study investigates the performance of merging radar and rain gauge data for different high temporal resolutions and rain gauge network densities.

Three different geostatistical interpolation techniques: Kriging with external drift, indicator kriging with external drift and conditional merging were compared and evaluated by cross validation. Ordinary kriging was considered as the reference method without using radar data. The study area is located in Lower Saxony, Germany, and covers the measuring range of the radar station Hanover. The data used in this study comprise continuous time series from 90 rain gauges and the weather radar that is located near Hanover over the period from 2008 until 2010. Seven different temporal resolutions from 10 min to 6 h and five different rain gauge network density scenarios were investigated regarding the interpolation performance of each method. Additionally, the influence of several temporal and spatial smoothing-techniques on radar data was evaluated and the effect of radar data quality on the interpolation performance was analyzed for each method.

It was observed that smoothing of the gridded radar data improves the performance in merging rain gauge and radar data significantly. Conditional merging outperformed kriging with an external drift and indicator kriging with an external drift for all combinations of station density and temporal resolution, whereas kriging with an external drift performed similarly well for low station densities and rather coarse temporal resolutions. The results of indicator kriging with an external drift almost reached those of conditional merging for very high temporal resolutions. Kriging with an external drift appeared to be more sensitive in regard to radar data quality than the other two methods. Even for 10 min temporal resolutions, conditional merging performed better than ordinary kriging without radar information. This illustrates the benefit of merging rain gauge and radar data even for very high temporal resolutions.

1. Introduction

Rainfall data with a high resolution in space and time are of importance for the modeling of hydrological and other environmental processes. Rainfall is usually measured at irregularly spaced point locations with a certain density. The spatial density is often quite high for daily measurements, but there is regularly a lack of stations delivering a more frequent recording of precipitation. Radar data have a high resolution in space and time, but are in general strongly biased (Seo et al., 1999). A radar device does not measure the precipitation intensity directly, but rather the reflected energy from hydrometeors at a certain height above the ground. Sources of errors include variations in the relationship between reflected energy and rainfall intensity depending on rainfall type, changes in the precipitation particles before reaching the ground, anomalous beam propagation and attenuation (Wilson and Brandes, 1979). Hence, it could be expected that the use of uncorrected radar data is not acceptable for many hydrological applications.

Considering only station data to obtain rainfall estimates, various interpolation methods have been applied (Dubois et al., 1998). A few examples include the nearest neighbor method (Isaaks and Srivastava, 1990), inverse distance weighting, spline fitting techniques (Hutchinson, 1998a,b) and univariate kriging approaches like ordinary kriging. Some of these methods create strongly smoothed areal rainfall distributions which usually do not represent the actual spatial rainfall structure. Multivariate geostatistical methods, e.g. kriging with an external drift, were applied in several studies by using additional information in order to improve the interpolation performance. For instance, Goovaerts (2000) reported that implementing the elevation as a background information can improve the interpolation performance on a monthly and yearly time scale.

As a result of improved availability and higher accuracy of radar data, several methods for merging rain gauge data and radar data

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were proposed over the years. Merging approaches based on cokriging were applied in numerical experiments by Krajewski (1987) and Azimi-Zonooz et al. (1989). The incorporation of simulated radar information improved areal rainfall estimations for simulated rainfall fields.

Haberlandt (2007) used kriging with an external drift to interpolate hourly rain gauge data, using radar as the drift information. A clear improvement of interpolation performance in comparison to univariate interpolation methods was achieved. However, the usage of elevation as further additional information did not improve the quality noticeably. Another study by Verworn and Haberlandt (2011) showed the benefit of implementing radar data in kriging as an external drift.

A further technique to combine radar and rain gauge data is the so called conditional merging approach, which consists of combining an interpolated rain gauge field with rainfall variability information derived from radar data. The method was reported first in Ehret (2003) and it is referred as Conditional Merging in Sinclair and Pegram (2005).

Goudenhoofdt and Delobbe (2009) evaluated several merging approaches with different complexity for daily rainfall data and preferred geostatistical merging over univariate rain gauge interpolation and radar data adjustment. Kriging with an external drift was the best approach. However, conditional merging performed only slightly worse. Velasco-Forero et al. (2009) evaluated ordinary kriging, kriging with an external drift and collocated cokriging in combination with a non-parametric and automatic technique to obtain correlograms from radar images. Kriging with an external drift performed best.

Statistical merging procedures were applied for combining rain gauge and satellite data as well. For instance, Li and Shao (2010) proposed a nonparametric kernel merging technique for rain gauge and TRMM satellite data. An improvement in comparison to kriging methods was detected for the Australian study area. Woldemeskel et al. (2013) used a combination of thin plate smoothed splines and inverse distance weighting to merge satellite and station data on a monthly time scale. In particular for regions with a sparse station network, an improvement of rainfall estimation was found out.

Bárdossy and Pegram (2013) used copula techniques and kriging methods for the spatial interpolation of rainfall sums for 1 day, 5 days, 1 month and 1 year, while taking into account the elevation as the additional information. The best interpolation results were achieved by using a shifted and smoothed version of the digital elevation model which accounts for the effects of directional advection. In general the copula-based techniques performed well for all temporal resolutions and provided a better estimation of uncertainty.

There are several uncertainties in the estimation of rainfall intensity by weather radar, e.g. variations of parameters in the Z–R-relationship in relation to rain type (Griffith, 1995), attenuation of the radar beam and increasing measuring altitude depending on the distance from the radar station. The occurrence of these errors is crucial for high temporal resolutions and becomes less important with increasing accumulation time. Due to this, it could be expected that the advantage of incorporating radar data would be restricted to lower temporal resolutions. Additionally, it is generally assumed that the benefit of using radar data would increase by decreasing rain gauge network density. This assumption is supported by findings of Krajewski (1987), Goudenhoofdt and Delobbe (2009) and Yoon et al. (2012), where station density effects had been analyzed.

A different way of tackling the problem of the merging rain gauge with radar data is the assimilation of radar information to rain gauge measurements. The error variance of various uncertainty sources could be quantified and incorporated in the calibration procedures (Chumchean et al., 2003, 2004).

The objective of this study is to compare the performance of certain merging techniques between gauge and radar rainfall for a large and continuous data set. Most of the previous studies, which included merging or other interpolation techniques, used daily or hourly data for a specific area with a certain number of available rain gauges. This study evaluates a wide range of high temporal resolutions from 10 min to 6 h and various station network densities. It aims at providing information for different temporal resolutions and station densities, about whether the combined use of rain gauge and radar data is advantageous compared to univariate rain gauge interpolation. Inspired by Bárdossy and Pegram (2013) it looks in particular at spatial and temporal smoothing options of the radar variable to improve the interpolation performance. In addition the effect of radar data quality on the merging result is investigated in this study.

The paper is organized as follows. After the Introduction, the section "Methodology" contains a description of all merging techniques that were applied for this study. Also, the general evaluation procedure followed in this case study and the performance assessment are explained. The study area and data are introduced in Section 3. In particular the radar data pre-processing is described here. Next, Section 4 contains the results and a corresponding discussion. The findings are presented separately for the effect of radar data smoothing on the interpolation performance and the influence of station density and temporal resolution. Moreover, radar data quality aspects are discussed here. In the final section the conclusions are drawn and an outlook is presented.

2. Methodology

2.1. Merging methods for radar and rain gauge data

The geostatistical approaches used in this study for merging rain gauge and radar data include Kriging with External Drift (KED), Indicator Kriging with External Drift (IKED) and Conditional Merging (CM). The univariate method Ordinary Kriging (OK) is used as a reference, illustrating a possible benefit of radar data use. A detailed description of OK is provided in geostatistical textbooks (Goovaerts, 1997; Isaaks and Srivastava, 1990). The Geostatistical Software Library (Deutsch and Journel, 1992) with some modifications for the successive procession of time series was used for the computations in this study.

All kriging methods require the assumption of a theoretical semivariogram model that is to be fitted to an experimental one. The semivariogram $\gamma(h)$, which will be referred as variogram in the following text, is a measure indicating the spatial variability of a regionalized variable Z.

$$\gamma(h) = \frac{1}{2 \cdot N(h)} \sum_{i=1}^{N(h)} (Z(u_i) - Z(u_i + h))^2, \tag{1}$$

where $N(h)$ is number of data pairs, which are located a distance vector (h) apart. Previous research of Haberlandt (2007) and Verworn and Haberlandt (2011) showed that the variogram model has only a small impact on the estimation performance of OK and KED, though the distribution of rainfall can be highly dynamic in space and time. Similar results regarding the variogram influence were obtained by Ehret (2003).

Accordingly, two isotropic variogram models were used. They were fitted to experimental variograms, which were averaged separately over all summer and all winter time steps. This separation into one summer and one winter variogram is considered because of the assumed seasonal changes in rainfall type. Only radar data were used for the calculation of experimental variograms. Germann and Joss (2001) also conducted variogram estimation using radar data and reported that high resolution radar images