ISPRS Journal of Photogrammetry and Remote Sensing xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Comparing methods for the approximation of rainfall fields in environmental applications

G. Patané [a,*], A. Cerri [a], V. Skytt [b], S. Pittaluga [a], S. Biasotti [a], D. Sobrero [a], T. Dokken [b], M. Spagnuolo [a]

[a] CNR-IMATI, Genova, Italy
[b] SINTEF, Oslo, Norway

A R T I C L E I N F O

Article history:
Received 15 February 2016
Received in revised form 5 August 2016
Accepted 16 September 2016
Available online xxxx

A B S T R A C T

Digital environmental data are becoming commonplace and the amount of information they provide is complex to process, due to the size, variety, and dynamic nature of the data captured by sensing devices. The paper discusses an evaluation framework for comparing methods to approximate observed rain data, in real conditions of sparsity of the observations. The novelty brought by this experimental study stands in the geographical area and heterogeneity of the data used for evaluation, aspects which challenge all approximation methods. The Liguria region, located in the north-west of Italy, is a complex area for the orography and the closeness to the sea, which cause complex hydro-meteorological events. The observed rain data are highly heterogeneous: two data sets come from measured rain gathered from two different rain gauge networks, with different characteristics and spatial distributions over the Liguria region; the third data set come from weather radar, with a more regular coverage of the same region but a different veracity. Finally, another novelty of the paper is brought by the proposal of an application-oriented perspective on the comparison. The approximation models the rain field, whose maxima and their evolution is essential for an effective monitoring of meteorological events. Therefore, we adapt a storm tracking technique to the analysis of the displacement of maxima computed by the different methods, used as a dissimilarity measure among the approximation methods analyzed.

1. Introduction

The large amount of digital data provides an extremely rich, yet difficult to process, amount of information about our environment, geographic and meteorological phenomena. The geographical area selected for presenting our results, the Liguria region in Italy, is an exemplary case study: the articulated orography is characterized by many small catchment basins that are highly influenced by local maxima of precipitation. Moreover, the proximity to the sea causes additional problems during storms, concurring to the creation of secondary low pressure areas, also known as the *Genova Low*, which increases the amount of precipitation and the risk of critical flash floods. The continuous observation of rain data during critical events, as well as the analysis of historical time series of precipitation, are definitely crucial to support a better understanding and monitoring of hydro-geological risks, such as floods and landslides (Keefer et al., 1987; Hong et al., 2007; Wake, 2013; Hou et al., 2014). A robust approximation method, resilient to errors, is therefore highly desirable.

In this context, the paper presents the results of the evaluation of six approximation techniques, which give insights into their suitability to capture the behavior of precipitation events: the nearest neighbor method, the piecewise linear approximation with barycentric coordinates, the inverse distance weighting, kriging, the Locally Refinable (LR) B-Splines, and the Radial Basis Functions (RBFs). The comparison of methods for rainfall approximation has been addressed in the literature both at the theoretical level (Scheuerer et al., 2013) and for domain-specific analysis (Skok and Vrhovec, 2006). Our study contributes to this topic extending the analysis to more approximation techniques, such as the LR B-Splines, and using a new setting for the comparison, inspired by the theory of *topological persistence* (Edelsbrunner et al., 2002). The basic idea is that, in order to characterize precipitation events, it is important to focus on the main features of the rainfall fields and their configuration. With this motivation in mind, the *prominence* of precipitation maxima is measured through the notion of

* Corresponding author.
E-mail addresses: patane@ge.imati.cnr.it (G. Patané), cerri@ge.imati.cnr.it (A. Cerri), vibeke.skytt@sintef.no (V. Skytt), pittaluga@ge.imati.cnr.it (S. Pittaluga), biasotti@ge.imati.cnr.it (S. Biasotti), sobrero@ge.imati.cnr.it (D. Sobrero), tor.dokken@sintef.no (T. Dokken), spagnuolo@ge.imati.cnr.it (M. Spagnuolo).

http://dx.doi.org/10.1016/j.isprsjprs.2016.09.011
0924-2716/

persistence, which allows for hierarchically organize maxima by importance, and possibly filter out irrelevant ones. Based on this, we developed an approach to compare different approximation methods based on the analysis of the number and location of the most prominent maxima they produce.

Our focus is on the evaluation of approximation performance in real conditions of sparsity: the number of the measuring gauges is quite low with respect to the area covered and their distribution is quite uneven. The evaluation results give also insights on the influence of integrating radar data in the approximation: rain data extracted from radar measures provide a complementary information with respect to rain gauges, less accurate but with a wider and more stable coverage. The integration of measured rain and radar data gives insights on the reliance on radar-driven approximations in case of failures of some rainfall stations during heavy storms.

For this study, we considered some of the best known methods in this field (nearest neighbor, piecewise linear, inverse distance weighting, kriging) and some other methods that have been applied mostly in the field of computer graphics, but have interesting properties for this application (LR B-Splines and RBFs).

The nearest neighbor method provides a rough approximation by defining the rainfall approximation at a point as equal to the rainfall value measured by its closest rainfall station. Barycentric coordinates are typically applied to compute piecewise linear approximations on triangle, or more generally, polygonal meshes, and they can be computed very efficiently, but generally provide a lower accuracy when we consider sparse data. LR B-Splines are particularly useful as a compact representation of functions over large domains: they use a (locally) regular domain parameterization and can be locally refined according to the required approximation error. The inverse distance weighting and ordinary kriging are very well-known approximation methods in this field. Ordinary kriging uses a variogram to capture the spatial distribution of the input data; similarly, RBFs use a kernel, which can be also adapted to the spatial distribution of the data, through the selection of the kernel width. Among other techniques, we mention Poisson based methods. The solution to the Poisson equation, which has been applied to surface reconstruction from point sets (Kazhdan et al., 2006), can be written in terms of the harmonic kernel. Therefore, Poisson methods provide results analogous to the approximation with RBFs induced by the harmonic kernel. Since the harmonic kernel tends to over-smooth the solution, in our experiments we will focus on the approximation with RBFs induced by the Gaussian kernel.

The aforementioned approximation methods define different functions, whose behavior is studied both at the numerical level (accuracy, sensitivity to sparseness, computational issues) and at a qualitative level by measuring the differences among the configuration of precipitation maxima induced by the six techniques. The comparative study was conducted selecting Liguria as area of interest, and two precipitation events recorded on September 29, 2013 and January 17, 2014, characterized by different meteorological situation and events. For the latter event, we also used rain data extracted from weather radar acquisition.

To contextualize better the comparison, we start with a short overview of related work on rain observation methods, approximation and comparison techniques (Section 2). We present the setting adopted for the evaluation with details on the rain event and metrics used for the comparison (Section 3). We give the formal definition of the six approximation methods discussed (Section 4) and discuss their performances with respect to accuracy, behavior with respect to sparsity, and computational aspects (Section 5). Then, the approximation schemes are compared by analyzing the difference in the configuration and prominence of the detected maxima (Section 6). Finally (Section 7), we summarize our study.

2. Related work

We briefly review previous work on measuring, approximating, and analyzing rainfall data and precipitation fields.

2.1. Measuring rainfall data

Rainfall intensities are traditionally derived by measuring the rain rate through rain gauges, weather radar, or by measuring the variations in soil moisture with micro-wave satellite sensors (Brocca et al., 2014). Even though satellite precipitation analysis allows the estimation of rainfall data at a global scale and in areas where ground measures are sparse, the evaluation of light rainfalls is generally difficult, thus generating an underestimation of the cumulated rainfalls (Kucera et al., 2013). To bypass this issue, in Brocca et al. (2014) the soil water balance equation is applied to extrapolate the daily rainfall from soil moisture data. The integration of rainfall data at regional and local levels is also intended to provide a more precise approximation of the underlying phenomenon on urban areas, which are sensitive to spatial variations in rainfalls (Segond, 2007). The combined use of rain height measured at rain gauges and radar-derived ones provides locally accurate but spatially anisotropic measures (around gauges) with globally distributed detailed data. Furthermore, we mention that the spatial and temporal variations (e.g., speed, direction) of rainfalls are important to characterize their variability and peaks, together with their effects on catchments.

2.2. Approximating rainfall data

Different approaches have been used for the approximation of rainfall data. In Thiessen (1911), rainfalls recorded in the closest gauge are associated with un-sampled locations, by identifying a Voronoi diagram around each weather station and assigning the measured rainfall to the respective Voronoi cell. Back to the 1972, the U.S. National Weather Service proposed to estimate the unknown rainfall values as a weighted average of the neighboring values; the weights are the inverse of the squares of the distances between the un-sampled locations and each rainfall sample. The underlying assumption is that the samples are autocorrelated and their estimates depend on the neighboring values. This method has been extended in Teegavarapu and Chandramouli (2005) through the modified inverse distance and the correlation weighting method, the inverse exponential and nearest neighbor distance weighting method, and the artificial neural network estimation. In McRobie et al. (2013), storms are modeled as clusters of Gaussian rainfall cells, where each cell is represented as an ellipse whose axis is in the direction of the movement and the rainfall intensity is a Gaussian function along each axis (Willems, 2001).

McCuen (1989) proposed the *isoyetal method* that allows the hydrologists to take into account the effects of different factors (e.g., elevation) on the rainfall field by drawing lines of equal rainfall depths among the rain-gauges and taking into account the main factors that influence the distribution of the rain field. Then, the rainfalls at new locations are approximated by interpolation starting from the isohyets. Geo-statistical approaches allow us to take into account the spatial correlation between neighboring samples and to predict the values at new locations (Journel and Huijbregts, 1978; Goovaerts, 1997; Goovaerts, 2000). Furthermore, the geo-statistic estimator includes additional information, such as weather-radar data (Creutin et al., 1988; Azimi-Zonooz et al., 1989) or elevation from a digital model (Goovaerts, 2000; Di Piazza et al., 2011).

Please cite this article in press as: Patané, G., et al. Comparing methods for the approximation of rainfall fields in environmental applications. ISPRS J. Photogram. Remote Sensing (2016), http://dx.doi.org/10.1016/j.isprsjprs.2016.09.011