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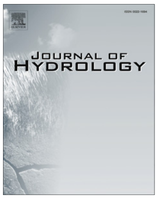

Mapping mean total annual precipitation in Belgium, by investigating the scale of topographic control at the regional scale

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SUMMARY

Accurate precipitation maps are essential for ecological, environmental, element cycle and hydrological models that have a spatial output component. It is well known that topography has a major influence on the spatial distribution of precipitation and that increasing topographical complexity is associated with increased spatial heterogeneity in precipitation. This means that when mapping precipitation using classical interpolation techniques (e.g. regression, kriging, spline, inverse distance weighting, etc.), a climate measuring network with higher spatial density is needed in mountainous areas in order to obtain the same level of accuracy as compared to flatter regions. In this study, we present a mean total annual precipitation mapping technique that combines topographical information (i.e. elevation and slope orientation) with average total annual rain gauge data in order to overcome this problem. A unique feature of this paper is the identification of the scale at which topography influences the precipitation pattern as well as the direction of the dominant weather circulation. This method was applied for Belgium and surroundings and shows that the identification of the appropriate scale at which topographical obstacles impact precipitation is crucial in order to obtain reliable mean total annual precipitation maps. The dominant weather circulation is determined at 260°. Hence, this approach allows accurate mapping of mean annual precipitation patterns in regions characterized by rather high topographical complexity using a climate data network with a relatively low density and/or when more advanced precipitation measurement techniques, such as radar, aren't available, for example in the case of historical data.

1. Introduction

Precipitation is widely recognized as an important factor controlling environmental processes and therefore forms an essential input variable in many applications aimed at predicting or investigating these processes. Some of these applications, such as models predicting avalanches or landslides (Nolin and Daly, 2006; Van Den Eeckhaut et al., 2006) require both the temporal and spatial scale of the input precipitation fields to be very detailed. Other applications, in contrast, such as regional land use models, biogeochemical cycle models (e.g. carbon storage) or models of the co-evolution of mountain ranges and climate systems only require very detailed spatial scales, while fairly coarse monthly or even annual temporal scales are sufficient (e.g. Daly et al., 1993; Kittel et al., 1997; Roe and Baker, 2006; Milne et al., 2007; Meersmans et al., 2012).

Recent studies (e.g. Parsons and Foster, 2011) have suggested that the spatial variability of long-term average precipitation might be fairly large even at a within field/(sub)catchment level (resolution < 1 km), consequently questioning the use of anthropogenic radionuclide Cesium (^{137}Cs), i.e. globally deposited following atmospheric nuclear-bomb tests in the past (mainly 1950–1960s), as a proxy for erosion (Parsons and Foster, 2011). Hence, identification of the resolution at which topography influences the spatial distribution of precipitation will be essential to evaluate the validity of commonly used precipitation fallout related radionuclide proxies (such as ^{137}Cs) at the landscape scale. One of the main reasons for the very large spatial variability of precipitation is its strong dependence on the terrain altitude and steepness as well as the orientation of the slopes. The literature indicates that even low elevation macro-relief structures can exhibit a significant effect on surface

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precipitation rates (e.g. Minder et al., 2008). An extensive review of the physical mechanisms leading to larger precipitation amounts over terrain has been given recently by for example Roe (2005) and Houze (2012). Houze (2012) describes at least two distinct mechanisms that could lead a pre-existing frontal cloud to be enhanced and produce a precipitation maximum on the upwind side of a low barrier. Firstly, the terrain could facilitate the gradual rise of warm air ahead of frontal systems, while at the lee side of the hill the precipitating capacity is weakened by the down-slope air motion (Houze, 2012). Secondly, the feeder-seeder mechanism could enhance precipitation rates onto a ridge. In this case, an upper-level cloud (the feeder) is producing precipitation, while a low, shallow, orographically-induced cloud (the seeder) could act to enhance the precipitation by accretion of the cloud droplets onto the precipitating particles from the cloud above. During summer, convective events also contribute significantly to the total rainfall in the region of interest (Roe, 2005). Convective events might be affected by low terrain in various ways, e.g. by triggering by lee-waves in the wake of a hill (Houze, 2012). By the mechanism listed above, low elevation barriers do have the potential to influence the dominant weather circulation and, therefore, could exercise a primary control on the regional spatial precipitation pattern in these environments.

Despite the widely recognized importance of the spatial distribution of precipitation over complex terrain, many regional climate inventories are based on long term observations from sparse meteorological stations. For example, relatively coarse precipitation maps are available at the national or continental scale, from the ATEAM project (Mitchell et al., 2004). Most often, point data are extrapolated to a continuous grid by using classical interpolation techniques, such as nearest neighbor methods, local linear regression, inverse distance weighting, spline or kriging methods (without or with external drift) (e.g. Goovaerts, 2000; Lloyd, 2005; Daly, 2006; Basistha et al., 2008; Tobin et al., 2011). In most cases these techniques are not satisfactory, since the spatial heterogeneity of precipitation and their resolutions are sub-optimal for ecological and environmental modeling. Mapping precipitation in regions characterized by complex topography, such as mountainous regions, demands higher density measurements in order to obtain a climate map with a spatially uniform quality level when using classical interpolation techniques (Daly, 2006). Nevertheless, the cost of monitoring at sufficient density may be prohibitive and there is, therefore, a need to develop strategies for interpolation of data that capture the structure of precipitation patterns, which will help in setting-up more efficient monitoring networks.

This has lead over the last decades to increased efforts in developing techniques to obtain a more accurate interpolation, based on elevation data (e.g. Sen and Habib, 2000; Lloyd, 2005; Di Luzio et al., 2008; Gottardi et al., 2012) or using the slope orientation of mountain ranges (e.g. Turner et al., 2009; Hughes et al., 2008). One of the most promising approaches to the characterization of topographic control on spatial patterns of precipitation is the Precipitation-elevation Regressions on Independent Slopes Model (PRISM) (e.g. Daly et al., 2002). In this model precipitation is interpolated for each grid cell of the digital elevation model (DEM) based on a simple weighted precipitation-elevation regression with distance to station, coastal proximity, general slope orientation and vertical layer (inversion layer or not) as weighting factors. In the application of PRISM, it is critical to understand at which scale precipitation is influenced by the topography. Daly et al. (2002) explored this question using 6 DEMs with a differing smoothing level, based on station data density and local terrain complexity.

Even more advanced techniques combine information obtained from weather radar with that from rain gauges. Goudenhoofdt and Delobbe (2009) showed that a recent technique based on the geostatistical merging of weather radar and rain gauges provides spatially and temporally accurate daily rainfall accumulation predictions. While this approach certainly has the potential to improve our understanding of the relation between topography and precipitation, the fairly recent advent of weather radars prohibits the application of this approach to historical data, long time periods or regions not covered by weather radar.

Hence, there is still a need for interpolation techniques of intermediate complexity to obtain reasonable estimates of surface precipitation with high spatial resolution, only based on information from rain gauges and terrain characteristics. One of the main caveats with techniques like PRISM, is that it is not known a priori what the optimal scale is of the input fields. In addition, information on the prevailing rain-bearing wind direction could be a significant improvement to PRISM. To overcome this shortcoming, recently Gottardi et al. (2012) conducted a novel methodology to map daily precipitation amounts in main mountain ranges in France (i.e. Pyrenees, Central Massif and Alps) by combining a local elevation–precipitation model (comparable to PRISM) with a weather pattern classification. They defined 8 different weather patterns (e.g. Southwest circulation or anticyclonic) and an associated linear orographic precipitation gradient. The gridded precipitation was a function not only of elevation, but also of the weather-pattern specific gradient, giving weights to neighboring stations using a “crossing distance” and taking into account crests and valleys between the stations and the grid cell of interest. While this method provides very detailed daily estimates of surface precipitation, it is also computationally expensive, given the identification of the weather pattern for each day.

This study discusses a novel, computationally affordable interpolation technique, using the dominant rain-bearing wind direction and the optimal scales of topographical variables, aimed specifically at regions with sparse data over terrain with intermediate complexity or to reconstruct very detailed historical precipitation maps. The scale at which relief influences precipitation will be investigated, and the direction of the dominant weather circulation identified. These two components form essential elements in the present novel spatial precipitation model approach, which will help us to support the hypothesis of the existence of a rain shadow effect in these environments. More specifically, this methodological framework will be applied to a specific case study, i.e. predicting average yearly precipitation (1960–1990) in Belgium and surroundings, including the Ardennes–Eifel massif situated at the Belgian–German border (Fig. 1).

2. Material and methods

2.1. Study area

The northern and western parts of Belgium are situated in the North-west European lowlands and are characterized mainly by altitudes less than 100 m above sea level. The Ardennes–Eiffel massif covers the eastern and southern part of the study area and reaches altitudes up to 700 m (Fig. 1A). The study area is characterized by a temperate maritime climate, with a mean annual temperature and total annual precipitation amounts ranging from about 10 °C and 700 mm in the west to about 6 °C and 1400 mm in the southeast.

Fig. 1B shows that the 30-year average annual precipitation amounts of the stations in Kall (860 mm yr^{-1}) and Nuerburg (872 mm yr^{-1}), situated in the eastern part of the Ardennes – Eiffel massif at altitudes of respectively 550 and 629 m asl, are remarkably low compared to the stations near the summit and/or situated on the western part at similar or even lower altitudes (e.g. La