

Dear prof. Seibert,

hereby we submit a revised version of our manuscript „Characteristics of rainfall events in RCM simulations for the Czech Republic“. The critical remarks of the referees and your suggestions resulted in substantial rewrite of the paper. Specifically we focused on highlighting the novelty of our contribution, clear description of the methods used and drawing the attention more to the methods and general results. We also considerably reduced the detailed description of specific results, especially those that are too focused on the study area. We believe that the paper has been substantially improved and thank you and the referees for comments and suggestions.

Best regards,

Referee #1

General comments

The paper evaluates the performance of an ensemble of regional climate models (RCMs) for simulation of heavy rainfall events for the Czech Republic. In recent years, a large number of papers have performed similar analyses of the performance of RCMs by (i) considering different RCMs with different spatial resolutions, (ii) studying different regions of the world, and (iii) analysing a range of rainfall characteristics. Much of this work has been referred to and discussed in the paper. However, the purpose of the current study and its contribution compared to state-of-the-art in this area is not clear. The authors state that “Characteristics of individual heavy rainfall events (such as event depth, duration, and intensity) in RCM simulations have not been studied to date” (Page 2, line 25-26). The authors may define rainfall characteristics differently than what has been done in other studies, but the novelty of this compared to the range of other rainfall characteristics that have been analysed in similar studies seems limited.

In line with the referee we admit that there has been a plethora of studies concerning the evaluation of various precipitation characteristics in global and regional climate models. The vast majority of these studies, however, focused on daily or longer temporal scales, while sub-daily model performance has received relatively little attention to date (Westra et al., 2014). Particularly, we are not aware of another study that would look in detail into *rainfall event* characteristics in RCMs (which are important with respect to hydrological impacts, as detailed below). The few existing studies on RCM-simulated sub-daily rainfall are typically looking at precipitation maxima in a number of temporal aggregations (Hanel and Buishand, 2010; Gregersen et al., 2013), dependence of RCM performance on its resolution (Prein et al., 2016; Sunyer et al., 2016), diurnal cycle of simulated hourly precipitation (Prein et al., 2015 and references therein) or scaling of precipitation extremes with temperature (Lenderink and van Meijgaard, 2008; Ban et al., 2015). Although some of these results can partly be related to rainfall event characteristics (e.g. performance of an RCM in simulating annual precipitation maxima may be related to that in simulating rainfall event maxima), they cannot address questions such as “is the depth of a simulated rainfall event comparable to that of a real event?”, “is the performance influenced by the rainfall depth itself?”, “are the simulated events of proper length and rain rate?” etc. The importance of these questions in evaluating climate models has been highlighted e.g. by Westra et al. (2014) who suggested (among other things) to focus on (spatial structure and) temporal evolution of rainfall events and their timing and intermittency.

Moreover, characteristics of rainfall events determine characteristics of various hydrological processes, e.g. overland flow generation and shape of the resulting hydrograph (Singh, 1997), soil moisture dynamics (Wang et al., 2008; He et al., 2012), infiltration (Ran et al., 2012), rainfall erosion (Wischmeier and Smith, 1978), evaporation (Dunkerley, 2008), storm sewer flow rates and direct runoff (Schilling, 1991; Giulianelli et al., 2006). Therefore information on changes in these characteristics is highly relevant for river basin management, urban hydrology, flood protection, erosion control etc. That is why we consider these characteristics important also in RCM evaluation studies.

Assessments of simulated precipitation at sub-daily time scales often face problems with data availability – sub-daily RCM simulations are in general not easily available and relevant (sub-daily) observational products allowing for comparison between RCMs (representing spatial averages) and observations (point measurements) are lacking. Deflation of maxima due to spatial averaging is well recognized and expressed by so-called areal reduction factors (Svensson and Jones, 2010). Clearly the spatial averaging also affects the rainfall event characteristics, however, any quantitative assessment is lacking in the literature.

The novelty of our study can be summarized in the following points:

- evaluation of simulated sub-daily precipitation using a large ensemble of RCM simulations from the ENSEMBLES and CORDEX projects
- development of a methodology allowing for comparison of RCM-simulated rain event (spatial) characteristics to (point) observations
- assessment of rainfall event characteristics, such as event depth, event duration, event rain rate, event maximum intensity and indices of rainfall erosivity, which are only indirectly related to commonly

considered indices and are relevant for river basin management, urban hydrology, flood protection, erosion control etc.

We agree that these points could be stated more explicitly in the manuscript, and therefore we elaborated them in the revised manuscript in detail.

This is confirmed by the fact that the main findings of the study do not provide any convincing new insights. In the Discussion (Section 5.3) the authors discuss their results and compare with previous studies. Basically, all their findings are in agreement with previous studies.

Our results are indeed consistent with previous studies, however, we also address points that have not been studied before, e.g. the frequency of heavy rainfall events within a year and the skill of climate models in representing the basic characteristics of temporal structure of sub-daily rainfall in particular. We agree that the discussion currently included in the manuscript is to a large extent focused on comparison with other studies instead of addressing the possible consequences for hydrological modelling and climate change impact assessment at short temporal scales in general. Such discussion is supplemented in the revised manuscript.

Detailed comments

The results are not presented in a clear and concise way. The Results section provides a detailed enumeration of results shown in the figures. This part should be more to the point and focus on main results.

In agreement with this point as well as concerns of Referee #2 we reduced the result section and clarified the methods description.

Referee #2

General comments

The paper compares the characteristics of heavy rainfall events from 23 RCMs with those of point and area-averaged observations in Czech Republic. The methods used to identify heavy rainfall characteristics and to average point observations are new and able to increase our insight about both simulated and observational rainfall events in the country. In general, the paper is well organized and simple to read but difficult to understand some of the approaches used by the authors.

As I think the most interesting part of the paper for non-local readers are the methods used in the present study, I suggest the authors to clarify Sections 3.1 and 3.3. For example, the sentences “Alternatively, the minimum event depth of a heavy rainfall event is chosen such that the number of heavy events is on average the same as for observations (=15 %). This approach is similar to the quantile mapping method used frequently for bias correction.” given in Section 3.1 is not clear. Or you might add a figure to section 3.3 showing the generated neighbourhoods for stations corresponding to at least one of the RCMs.

We agree that the methods and key findings are more relevant for international readers than the detailed results. Therefore we revised the manuscript with focus on highlighting the novelty of our contribution, clear description of the methods used and drawing the attention more to the methods and general results. We also considerably reduced the detailed description of specific results, especially those that are too focused on the study area.

Minor points

Page 2 line 2: Please add more recent studies such as: Danandeh Mehr, A. and Kahya, E. (2016). Grid-based performance evaluation of GCM-RCM combinations for rainfall reproduction. Theoretical and Applied Climatology (in press)

Page 3 line 5: Please provide full expression before the abbreviation a.s.l.

Page 3 line 6: Please replace “the 1961-2000 period” with “the period 1961-2000”

This was corrected.

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Characteristics of rainfall events in RCM simulations for the Czech Republic

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Abstract. Characteristics of rainfall events in an ensemble of 23 regional climate model (RCM) simulations are evaluated against observed data in the Czech Republic for the period 1981–2000. Individual rainfall events are identified using the concept of minimum inter-event time (MIT) and only heavy events during the warm season (May–September) are considered. Inasmuch as an RCM grid box represents a spatial average rather than a point measurement, the effects from of areal averaging of rainfall data on characteristics of events are investigated using the observed data. Rainfall events from the RCM simulations are then compared to those from the at-site and area-average observations. Simulated number of heavy events and seasonal total precipitation due to heavy events are on average represented relatively well despite the higher spatial variation compared to observations. RCM-simulated event depths are comparable to the area-average observations, while event durations are overestimated and other characteristics related to rainfall intensity are significantly underestimated. The differences between RCM-simulated and at-site observed rainfall event characteristics are in general dominated by the biases of the climate models rather than the areal-averaging effect. Most of the rainfall event characteristics in the majority of the RCM simulations show a similar altitude-dependence pattern as in the observed data. The number of heavy events and seasonal total precipitation due to heavy events increase with altitude, and this dependence is captured better by the RCM simulations with higher spatial resolution.

1 Introduction

~~Not only are such characteristics of heavy rainfall events as event depth, duration, or intensity relevant for urban hydrology (e.g. Einfalt et al., 1998; Barbosa et al., 2012; Willems et al., 2012) or soil erosion assessment studies (e.g. Angulo-Martínez and Beguería, 2009; Meusburger et al., 2012; Todisco, 2014), they also influence such hydrological processes involving vegetation as interception, throughfall, and stemflow (e.g. Staelens et al., 2008; Siegert and Levia, 2014; Lozano-Parra et al., 2015). Moreover, potential~~

Potential changes in characteristics of precipitation events due to climate change may have significant societal impacts, especially when daily extreme rainfall intensity increases. Several studies have reported significant changes in daily precipitation extremes in observed data (e.g. Alexander et al., 2006; Trenberth, 2011; Westra et al., 2014). ~~Short duration as well as~~

in climate model projections (e.g. Kyselý et al., 2011; Hanel and Buishand, 2012; Madsen et al., 2014). It is argued that the intensity of short-duration extreme events in particular might intensify-increase more in future climate due to dynamical feedbacks (Lenderink and van Meijgaard, 2008; Berg and Haerter, 2013; Millán, 2014). Despite their importance, however, only a few studies have dealt with the characteristics of individual rainfall events derived from observed rainfall data (Fiener et al., 2013; Hanel et al., 2016). A comparative review of the published rainfall event characteristics has been provided by Dunkerley (2008a).

Many studies of precipitation extremes across Europe examine daily data from regional climate model (RCM) simulations (e.g. Jacob et al., 2007; Fowler and Ekström, 2009; Herrera et al., 2010; Hanel and Buishand, 2011, 2012). Although in recent years growing attention has been given to studies at sub-daily time scales (Hanel and Buishand, 2010; Arnbjerg-Nielsen, 2012; Kendon et al., 2012; Gregersen et al., 2013; Chan et al., 2014a; Kendon et al., 2014; Sunyer et al., 2015), the complexity of physical processes related to sub-daily extremes (Stocker et al., 2013; Siler and Roe, 2014) and their simplification within climate model parameterizations might discourage researchers from verification of sub-daily simulated precipitation. The lack of long and high-quality observed rainfall data series at hourly or sub-hourly time scales presents another barrier to verification (Westra et al., 2014).

The climate change scenarios for precipitation are frequently based on simulations of regional climate models (RCMs). Even as the majority of RCM simulations available are conducted in resolution coarser than 10 km, the convective processes associated with extreme-heavy rainfall actually develop at much finer scales (< 4 km; Prein et al., 2015). RCMs usually rely, therefore, on convection parameterization schemes, even though these are known sources of significant uncertainties and errors (Brockhaus et al., 2008; Hohenegger et al., 2008; Kendon et al., 2012). That is especially the case for the simulated sub-daily precipitation (Westra et al., 2014).

For the Czech Republic and an ensemble of RCMs, Kyselý et al. (2016) reported that underestimation of convective and overestimation of stratiform precipitation extremes result in a relatively good representation of total daily precipitation extremes. This had been noted also for other regions, including the the Netherlands (Hanel and Buishand, 2010) and Denmark (Gregersen et al., 2013). Moreover, the intensity of convective precipitation and total depths in summer were underestimated (more so in lowlands; Kyselý et al., 2016). Underestimation of summer precipitation totals was reported also by, for example, Hanel and Buishand (2012) (for the Czech Republic) and Rauscher et al. (2010) (for the region Eastern Europe). Kjellström et al. (2010) indicated that agreement between RCMs and observations at daily time scales was best for moderate rainfall intensities and that bias was increasing for heavier rainfall events. The ability of RCMs to represent hourly rainfall extremes properly has been questioned in several studies (e.g. Hanel and Buishand, 2010; Gregersen et al., 2013; Kendon et al., 2014). For instance, Hanel and Buishand (2010) found that 1-maxima were underestimated (compared to those from radar data) in most of those RCM simulations which they analysed for the Netherlands. Many studies of precipitation extremes across Europe examine daily data from RCM simulations (e.g. Fowler and Ekström, 2009; Herrera et al., 2010; Hanel and Buishand, 2011, 2012; Rajczak et al., 2013; Bartholy et al., 2015; Danandeh Mehr and Kahya, 2016). Although growing attention has been given to studies at sub-daily time scales in recent years, the complexity of physical processes related to sub-daily extremes (Stocker et al., 2013; Siler and Roe, 2014) and their simplification within climate model parameterizations might discourage

researchers from assessment of simulated sub-daily precipitation, particularly since its validation is impaired by the lack of long and high-quality observed rainfall data series at hourly or sub-hourly time scales (Westra et al., 2014).

Characteristics of individual

The existing studies on RCM-simulated sub-daily rainfall are typically looking at precipitation maxima in a number of temporal aggregations (Hanel and Buishand, 2010; Gregersen et al., 2013; Sørup et al., 2016), dependence of RCM performance on its resolution (Prein et al., 2016; Sunyer et al., 2016), diurnal cycle of simulated hourly precipitation (Prein et al., 2015 and references therein) or scaling of precipitation extremes with temperature (Lenderink and van Meijgaard, 2008; Ban et al., 2015; Martinková and Hanel, 2016), while studies looking in detail into individual rainfall event characteristics in RCM simulations are missing despite the fact that such characteristics of heavy rainfall events (~~such~~ as event depth, duration, and intensity) in RCM simulations have not been studied to date. Therefore, the or intensity are relevant for urban hydrology (e.g. Einfalt et al., 1998; Barbosa et al., 2012; Willems et al., 2012) and determine characteristics of various hydrological processes as overland flow generation and shape of the resulting hydrograph (Singh, 1997), soil moisture dynamics (Wang et al., 2008; He et al., 2012), infiltration (Ran et al., 2012), rainfall erosion (Wischmeier and Smith, 1978), evaporation (Dunkerley, 2008a), storm sewer flow rates and direct runoff (Schilling, 1991; Giulianelli et al., 2006). Therefore considering these individual rainfall event characteristics is important also in RCM evaluation studies, which has been highlighted already e.g. by Westra et al. (2014) who suggested (among other things) to focus on (spatial structure and) temporal evolution of rainfall events and their timing and intermittency. Despite their importance, however, only a few studies have dealt with the characteristics of individual rainfall events even in observed rainfall data (Fiener et al., 2013; Hanel et al., 2016a).

The purpose of this study is to assess heavy rainfall event characteristics in an ensemble of RCM simulations using hourly data conducted within the ENSEMBLES (van der Linden and Mitchell, 2009) and EURO-CORDEX (Jacob et al., 2014) projects. ~~The~~ Assessments of simulated precipitation at sub-daily time scales often face problems with data availability. Sub-daily RCM simulations are in general not easily available and relevant (sub-daily) observational products allowing for direct comparison between RCMs (representing spatial averages) and observations (point measurements) are lacking. Deflation of maxima due to spatial averaging is well recognized and expressed by so-called areal reduction factors (Svensson and Jones, 2010). Clearly the spatial averaging also affects the rainfall event characteristics, however, any quantitative assessment is lacking in the literature. The methodology allowing for comparison of RCM-simulated rainfall event (spatial) characteristics to (point) observations is presented in the study when the simulated rainfall events are compared to area-average observations in the Czech Republic for the validation period 1981–2000.

The paper is organized as follows: Section 2 describes the study area, as well as the observed and RCM-simulated data. Section 3 presents the definition of rainfall events, the event characteristics considered, and the approaches for assessing areal-averaging effects and biases in the RCM simulations. Results concerning the effects from areal averaging of rainfall data on on rainfall events and evaluation of RCM-simulated rainfall event characteristics are presented in Sect. 4 and discussed in Sect. 5. Key findings are summarized in Sect. 6.

2 Study area and data

2.1 Study area

Rainfall event characteristics are analysed for the Czech Republic (78,800 km²), located in Central Europe (Fig. 1a). Orography of the country varies considerably. As can be seen in Fig. 1b, approximately two-thirds of the area is situated at altitudes below
5 500 m above sea level (a.s.l.), even as several mountain ranges exceed 1200 m a.s.l.

Average annual precipitation totals for the ~~1961–2000 period~~ period 1961–2000 vary from about 420 mm in the central-western part of the country to more than 1200 mm in the mountains. Mean annual precipitation for the Czech Republic is about 670 mm, with a single maximum occurring at most stations in June and July (Tolasz, 2007). If averaged across the
10 Czech Republic, almost two-thirds of the annual precipitation falls in the warm half of the year. Rainfall events during the warm period (April–September) are usually of shorter duration and greater intensity. Rainfall or snowfall events during the cold half of the year (October–March), meanwhile, are mainly characterized by lower intensities and longer durations, and these are associated with passing frontal systems and pressure lows (Tolasz, 2007).

2.2 Observed precipitation data

In the present study, we used hourly precipitation data provided by the Czech Hydrometeorological Institute. The original data
15 in 10 min resolution are based on digitized pluviograph records (from float-type self-recording pluviographs with interception area of 250 cm²) and were quality checked by Květoň et al. (2004), who identified and reconstructed damaged or missing pluviograph records while considering many sources of rainfall information. Hanel and Máca (2014) had further assessed the quality of the reconstructed data set by comparing daily precipitation depths aggregated from 10 min data with daily precipitation depths from standard ombrometers. They had considered data for a day unreliable when the difference exceeded
20 1.5 mm for daily precipitation totals below 15 mm or 10 % for daily precipitation totals above 15 mm. The years with the fraction of unreliable records larger than 10 % were excluded from the data set. These same criteria were applied in the present study.

Given the unreliability of the pluviograph records in the winter period (Květoň et al., 2004), when large part of the precipitation falls as snow, only records from May to September have been considered. This period is hereinafter referred
25 to as the “season”. Only stations with at least 10 years of reliable data were used for the comparison of RCM-simulated and observed rainfall event characteristics in the validation period 1981–2000. The validation period was set to just 20 years in order to maximize overlap of the available RCM simulations (Sect. 2.3) and observed data. In total, 154 stations (with density of 1 station per 512 km²) fulfilled this condition. ~~(Meanwhile, more~~ More than 15 years of reliable data were available for 60 stations.)

30 In order to increase the number of stations available for spatial averaging, a longer period (1961–2009) was considered for analysing the areal-averaging effects. This resulted in making 26 additional stations available (each of which has records shorter than 10 years or ending before 1981). Figure 1b shows all 180 stations from the data set, the density of which came to approximately 1 station per 438 km².

Moreover, we examined the influence of the number of stations considered in the areal averaging using a dense rain gauge network for Prague (22 stations within 500 km²). Hourly precipitation data for the period 2002–2011 were provided by Pražská vodohospodářská společnost a.s., administrator of the Prague water management property.

2.3 RCM simulations

5 An ensemble of 23 RCM simulations was examined (see Table 1 for an overview). Six RCMs were driven by 14 global climate models (GCMs) to produce 19 simulations in total. Two RCMs (with a total of four runs) were also driven by ERA40 (Uppala et al., 2005) or ERA-INTERIM (Dee et al., 2011) reanalysis.

The RCMs' outputs are available on a rotated latitude–longitude grid with horizontal resolutions ranging from 12.5 to 50 km (Table 1). Only the CLM simulation is on a regular grid. From each RCM simulation only grid boxes covering the area of
10 the Czech Republic (i.e. 52–607 grid boxes for different resolutions and RCMs) were selected.

The HIRHAM5, HadRM3, and RACMO2 simulations were conducted within the ENSEMBLES project (van der Linden and Mitchell, 2009), while the RCA4 and RACMO22E simulations ~~were~~ within the EURO-CORDEX project (Jacob et al., 2014). Two of the HadRM3 simulations were driven by the GCM ~~version~~ versions with perturbed physics parameterizations (Collins et al., 2006). HadCM3Q0 is an unperturbed model run, HadCM3Q3 is a version with a low sensitivity to external forcing, and
15 HadCM3Q16 includes perturbations resulting in high sensitivity to external forcing. The perturbations in the HadRM3 RCM correspond to those in the HadCM3 GCM.

3 Methods

This section defines rainfall events in the observed and RCM-simulated data (Sect. 3.1) and describes those event characteristics considered (Sect. 3.2). Inasmuch as the RCM data represent areal averages rather than point values, the methods for assessing
20 the effect on event characteristics from areal averaging of rainfall data are further described in Sect. 3.3. Finally, approaches taken in evaluating simulated rainfall events are presented in Sect. 3.4.

3.1 Rainfall event definition

Several methods exist for defining individual rainfall events (e.g. Peters and Christensen, 2006; Ignaccolo and Michele, 2010; Gaál et al., 2014). One approach frequently used involves the concept of minimum inter-event time (MIT), which defines events
25 on the basis of a minimum time interval – reached or exceeded – between two individual events (Dunkerley, 2008b; Ignaccolo and Michele, 2010). The value of MIT should be selected so that the rainfall events are independent. ~~Nevertheless~~ In practice, ~~however,~~ MIT is often set on an ad hoc basis, for instance by following ~~another~~ well-established ~~method~~ methods such as the ~~universal soil loss equation~~ Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978).

~~Although the estimated optimal MIT would generally vary between the RCM simulations and across the area, and because~~
30 ~~the~~ The value of MIT ~~influences the values of rainfall events characteristics, a constant MIT is required~~ considerably influences rainfall event characteristics (Dunkerley, 2008b). For instance, for the observed sub-daily precipitation in the Czech Republic,

Hanel and Máca (2014) reported a 40 % decrease of event rainfall rate and more than 10 fold increase in event depth and duration with increasing MIT from 30 min to 24 h. As a consequence, in order to provide comparable characteristics (e.g. Dunkerley, 2008b; Hanel and Máca, 2014) rainfall event characteristics, MIT should not vary among RCM simulations (and observed data). Therefore, a 6 h MIT was used for deriving rainfall events within this study for all RCM simulations as well as for the observed data throughout this study. It should be noted that although this value is lower than the optimal MITs estimated for the Czech Republic by Hanel and Máca (2014), it is one of the values most frequently used (Dunkerley, 2008b). Similarly as in the USLE methodology, we considered further only the heavy rainfall events –

Using the MIT concept for determination of individual events requires choice of the wet-hour threshold (i.e. at-site events with total depth greater than 12.7 mm (Wischmeier and Smith, 1978) – precipitation amount below which the hour is considered dry). For the observed data, the minimum wet-hour depth is related to choice often follows naturally from rain gauge precision (leading frequently to wet-hour threshold of 0.1)mm h⁻¹ (Dunkerley, 2015). In the case of RCM simulations, very small amounts of rainfall are simulated for most of the intervals (due to drizzling effect) and the smallest non-zero precipitation value, when used as the wet-hour threshold, would lead to excessively long events. Therefore, 0.1 mm h⁻¹ was considered as the wet-hour threshold for the observed data as well as the RCM simulations in our study. The same wet-hour threshold as used here had been applied also for RCM simulations in previous studies previously (e.g. Willems and Vrac, 2011; Kendon et al., 2014; Sunyer et al., 2016). Although the same minimum event depth could be taken for RCM simulations as for observations (

Our attention is aimed only at events potentially causing soil erosion or flooding (denoted heavy rainfall events further). The identification of such events was based on one of the criteria used in USLE, i.e. considering only those events with total depth larger than 12.7 mm), it is well known that the RCM-simulated precipitation totals are often biased. As a consequence, the number of selected events might be influenced by the bias in mean precipitation. Alternatively, the minimum event depth of a heavy rainfall event is chosen such that the number of heavy (Wischmeier and Smith, 1978) . For the observed precipitation this leads to selection of ≈ 15 % of events is on average the same as for observations with the largest event depths. The same fraction of events according to event depth was considered as heavy rainfall events in each RCM simulation. Note that we preferred to determine the simulated heavy rainfall events as a fraction of events (≈ 15 %). This approach is similar to the quantile mapping method used frequently for bias correction.

To summarize, the areal heavy rainfall events (in RCM simulations and area-average observations) are here defined while considering a 6 h MIT, fixed wet-hour threshold of 0.1 mm with largest event depths) rather than as events with depth above a fixed threshold (12.7 mm, and minimum event depth corresponding to the 0.85 quantile of the distribution of event depths), since because of inherent bias in RCM simulations there might be too many or too few (even none) events exceeding this threshold.

3.2 Rainfall event characteristics

We focused on the following basic characteristics of rainfall events:

- event depth D [mm],
- event duration T [h],
- event mean rainfall rate R [mm h⁻¹]:

$$R = \frac{D}{T}, \text{ and} \quad (1)$$

- 5 • maximum 60 min rainfall intensity during ~~the~~ an event I_{60} [mm h⁻¹].

As our definition of a rainfall event is in general consistent with the USLE methodology, we consider also indicators of rainfall event erosivity:

- event rainfall energy E [MJ ha⁻¹] (Brown and Foster, 1987):

$$E = \sum_{t=1}^T 0.29d_t[1 - 0.72 \exp(-0.05d_t)], \quad (2)$$

10 where d_t is rainfall volume during hour t , and

- event rainfall erosivity index EI_{60} [MJ mm ha⁻¹ h⁻¹]:

$$EI_{60} = E \cdot I_{60}. \quad (3)$$

Note that in the USLE methodology, maximum 30 min rainfall intensity is ~~considered~~ used in eq. 3. Due to the temporal resolution of RCM-simulated data ~~used~~ in this study, we instead consider maximum 60 min rainfall intensity during an event
15 (I_{60}). The E and EI_{60} indices are ~~considered~~ assessed here not in order to quantify soil loss but rather as indicators ~~as to~~ of the erosive potential of a rainfall event.

In addition to the aforementioned rainfall event characteristics, we analysed also the following seasonal (May–September) characteristics:

- number of heavy rainfall events per season N_{se} [–], and
- 20 • seasonal total precipitation due to heavy rainfall events S_{se} [mm].

3.3 Areal averaging of rainfall data

Areal averaging of rainfall data can significantly affect such characteristics of ~~the events as depths~~ rainfall events as depth (Svensson and Jones, 2010) or intensity (Eggert et al., 2015). Because an RCM grid box represents a spatial average, RCM simulations cannot be compared directly to at-site observations. Therefore, various gridded data sets are used for validation
25 of RCM data (e.g. the E-OBS data set for Europe; Haylock et al., 2008). ~~The Unfortunately, the~~ gridded data sets available are limited to daily or longer temporal resolution and cannot be used for validation of sub-daily RCM simulations. Therefore,

analogously to the well-established areal reduction factors describing the decrease in rainfall/runoff maxima with increasing averaging area (e.g. Svensson and Jones, 2010), we quantified the effect that the areal averaging of rainfall data has on the rainfall event characteristics.

To assess this effect on the (event and seasonal) characteristics, we compared characteristics of events in area-average and
5 This quantification was based on comparison of rainfall event characteristics derived for observed at-site observed data data (further at-site characteristics) to those derived for area-average data (further area-average characteristics) with averaging area corresponding to the resolution of RCM simulations. Obviously we were able to calculate the area-average characteristics only at locations with dense station network.

The whole procedure can be summarized as follows:

- 10 1. Square neighbourhoods regions with area corresponding to the considered resolutions (12.5, 25, and 50 km) were defined around each station. ~~Neighbourhoods with~~ (the regions are further referred to as “neighbourhoods”). Each neighbourhood thus included one (the central) or more stations. Neighbourhoods including only one station were excluded from the analysis. This resulted in 36 neighbourhoods for the 12.5 km resolution (Fig. 1b), 118 for the 25 km, and 180 for the 50 km resolution. ~~Average numbers~~ The average number of stations included in the neighbourhoods
15 were was 2.25 for the 12.5 km, ~~2.9~~ 2.90 for the 25 km, and 6.04 for the 50 km resolution.
2. ~~Areal average rainfall was~~ Time series of areal average rainfall were calculated for each neighbourhood by averaging the data from included stations (for periods where station data sets overlapped). Rainfall events were determined and the rainfall event characteristics calculated for this areal average as well as at-site for the central station. ~~Characteristics of rainfall events were then calculated (hereafter referred to as “area-average” and “at-site” characteristics, respectively).~~
- 20 3. ~~We~~ To quantify the difference between the area-average and at-site characteristics at each neighbourhood, we evaluated the following indices ~~:~~ describing the differences in mean as well as in the whole distribution of rainfall event characteristics:
 - (a) Ratio of ~~areal mean (event and seasonal) characteristics for each neighbourhood to the~~ mean areal to mean at-site (event and seasonal) characteristics, ~~averaged over all neighbourhoods in the Czech Republic~~. This ratio is further
25 denoted rt_m .
 - (b) Ratio of the p^{th} quantiles of ~~event characteristics for each neighbourhood~~ areal event characteristics to the p^{th} quantiles of at-site event characteristics, ~~averaged across all neighbourhoods in the Czech Republic for~~ with $p = 0.05, 0.1, \dots, 0.95$. This ratio is referred to as quantile ratio rt_p .
 - (c) Ratio of ~~seasonal frequencies (averaged across the Czech Republic) for~~ frequencies of corresponding bins of the
30 histograms of areal and at-site event characteristics, further denoted as histogram ratio rt_f .

3.4 Evaluation of RCM-simulated characteristics of rainfall events

The RCM-simulated event characteristics (~~i.e. their representing~~ areal averages) were compared to the observed at-site characteristics ~~in a manner similar to that considering the same indices as~~ described in point 3 ~~of the procedure specified~~ in Sect. 3.3 ~~by but~~ replacing the observed areal average (event and seasonal) characteristics ~~for the neighbourhoods with the values~~
5 ~~for individual~~ ~~with the simulated characteristics for individual RCM grid boxes.~~ ~~To allow for assessment of grid boxes not including any station,~~ the mean, p^{th} quantiles and bin frequencies for the at-site characteristics were averaged over the whole ~~Czech Republic prior to the calculation of the ratios.~~

~~We note that the ratios between the RCM simulations~~ ~~The ratios between the RCM-simulated~~ and observed at-site rainfall ~~combine characteristics represent the combination of~~ the bias in the RCM simulation with the effect of areal averaging of
10 rainfall data. Therefore, ratios for RCM-simulated characteristics were further compared to those for area-average observations.

Finally, we also ~~examined~~ ~~evaluated~~ the dependence of the RCM-simulated (event and seasonal) characteristics on altitude. A linear regression model of the dependence of the p^{th} quantile (for p from 0.05 to 0.95) of the distribution of event characteristics on altitude was fitted ~~while considering the RCMs and for the RCM as well as the~~ at-site data. Altitude dependence of rainfall event characteristics was then ~~examined~~ ~~expressed~~ as the change of a characteristic per 100 m ~~change in elevation altitude~~
15 ~~difference~~ (y_p) given by:

$$y_p = \frac{100\beta + \alpha}{\alpha} \frac{100\beta_p + \alpha_p}{\alpha_p} \cdot 100 [\%], \quad (4)$$

where ~~β~~ ~~β_p~~ is the slope coefficient and ~~α~~ ~~α_p~~ is the intercept ~~for the linear regression between the p^{th} quantile of the event characteristics and altitude~~. Moreover, the values of the estimated slope coefficient (β) were analysed for the seasonal characteristics.

20 4 Results

This section presents findings related to areal averaging of rainfall data (Sect. 4.1). Further, the RCM-simulated rainfall event characteristics are evaluated with respect to the observed data for the validation period (1981–2000) using ratios of mean characteristics (rt_m ; Sect. 4.2), quantile ratios (rt_p ; Sect. 4.3), and histogram ratios (rt_f ; Sect. 4.4). Altitude-dependence of event characteristics considering the RCM simulations and at-site observations is assessed in Sect. 4.5.

25 4.1 Effects of areal averaging in the observed data

The number of ~~rainfall events in area-average observations is higher than that for the at-site data. The same holds true for the number of area-average heavy rainfall events (N_{se}) for the three spatial resolutions considered (Table 2, top four rows), which is on average in area-average observations is~~ approximately 1.4–2 events per season ~~higher~~ (i.e. ~~by as much as ca~~ 26 %) ~~than the number of higher than that for the~~ at-site ~~events~~ data for all considered spatial resolutions (Table 2, top four rows).

Minimum event depth (~~based on the 85th quantile of event depths defining the top 15 % of events (the heavy rainfall events)~~ for area-average observations is lower than 12.7 mm (the value for the at-site data), and ~~that this~~ results in smaller average event depths (D) compared to ~~these those~~ for the at-site observations. Smaller D are compensated, however, by a higher number of events (N_{se}), and that leads to a good representation of seasonal totals due to heavy rainfall events (~~S_{se} ; +3 % for area-average observations on average~~).

Mean characteristics of rainfall events considered for the at-site and area-average observations are shown in the right part of Table 2. Observed area-average characteristics are in general lower than at-site characteristics: D by 14–19 %, T by 8–18 %, R by 10–27 %, and I_{60} by 23–39 %.

The quantile ratios rt_p are shown in Fig. 2. Because in general the spread of the quantile ratios is similar for the spatial resolutions considered (not shown), only the envelope of rt_p ~~for all neighbourhoods~~ representing the maximum range between the 5th and 95th quantiles ~~from all neighbourhoods~~ for the three spatial resolutions is indicated by grey areas in Fig. 2 –

~~in addition to the mean quantile ratios for individual resolutions (given by lines)~~. Area-average event depths (D) are \approx 10–20 % smaller than at-site D for the whole range of event depths. ~~The area-average duration (T) of short events is comparable to the at-site T for the 12.5 and 25 km resolutions and larger (by \approx 20 %) for the 50 km resolution. For long events, the area-average T is about 16 % shorter compared to the at-site observations~~ ~~For the rest of the characteristics the intensity of the area averaging effect is in general stronger for larger quantiles of the distribution (leading to lower values of characteristics)~~. The area-average rainfall rate (R) is ~~event characteristics are~~ similar to the at-site ~~observations for low values and then significantly diminishes with increasing rainfall rate~~. ~~The remaining area-average characteristics' values are lower than those of the at-site observations, and the differences are larger for higher quantiles~~ ~~characteristics only for the duration (T) of short events and rainfall rate (R) of less intense events~~.

To demonstrate how spatial resolution influences the area-average characteristics, boxplots of rt_m for the area-average observations are presented as a part of Fig. 3 (grey boxplots in the right part of each panel). Most of the area-average characteristics decrease with increasing area. The exception is event duration (T), which increases with area, ~~and seasonal characteristics (number of heavy rainfall events and total precipitation due to these events) which are rather resolution independent~~. The differences ~~in mean event characteristics between the considered spatial resolutions~~ are generally small (less than 10 %), with the exceptions of R , I_{60} and EI_{60} ~~(at 17, 16, and 21 up to 20 %, respectively)~~. ~~These differences are considerably smaller, however, than are the differences between the event characteristics over the study area~~.

4.2 Simulated mean (event and seasonal) characteristics

Figure 3 presents boxplots of rt_m ratios between the RCM-simulated and observed at-site rainfall event characteristics for the validation period (1981–2000) as derived for grid boxes over the study area.

In the RCM simulations, the event depths (D) correspond generally well with the area-average observations (20 % smaller on average compared to at-site observations). Event duration (T) is longer for most of the RCM simulations than for at-site observations (on average by 18 %). That is in contrast with the area-average observations, for which the event duration (T) is shorter than for at-site observations ~~(by 13 % on average)~~. Because event depths (D) for the RCM simulations are smaller

than for at-site observations and event durations (T) are longer in general, event mean rainfall rates (R) are significantly lower compared to the at-site characteristics (by 56 % on average) while R for area-average observations are lower only by 17 % on average. Other characteristics' values, too, are. Other event characteristics are also significantly lower for RCM simulations compared to both the area-average and the at-site characteristics. For example, maximum 60 min rainfall intensities during an event (I_{60}) are lower by 30 % with respect to the area-average observations and by 69 % on average with respect to the at-site data. the observed characteristics.

The number of heavy events per season (N_{se}) is in general higher in the RCM simulations compared to the at-site observations (by 42 % (ca 16 % on average, i.e. 3.2 events per season). That difference is only 16 % (less than 1.5 events per season); however, when compared to the area-average observations. The differences in S_{se} between the RCM simulations and both at-site and area-average observations range from -33 to +48 % (+11 % on average, i.e. 23 mm per season compared to the area-average observations). For-

Note that the differences in seasonal and event characteristics may be considerably larger for individual RCM simulations, in particular at grid boxes with high altitude. For instance N_{se} and S_{se} in the two HIRHAM5 simulations (H5_BCM and H5_ECHAM5), large outliers are present at the grid boxes with the highest altitude (in the northern part of the Czech Republic). There, the number of simulated heavy events (N_{se}) reaches to approximately 44 per season and the seasonal total precipitation due to heavy events (S_{se}) to approximately 1700 mm. For observations (both at-site and area-average), maximum values are given by stations at highest altitudes, as well, but the maximum N_{se} is 16 and that for S_{se} is ≈ 500 mm. Moreover, several other outliers with higher values for the characteristics are present in the RCM simulations (especially for event depths and energies; not shown in Fig. 3). These outliers, too, are generally linked to grid boxes with the highest altitudes are more than three times larger than the observed characteristics at corresponding grid boxes.

The coefficient of variation (CV; not shown) of rt_m for the RCM grid boxes (indicator of spatial variability) corresponds relatively well with that of the area-average observations for event depth (D ; CV about 9 % on average), duration (T ; about 12 %), rainfall rate, maximum 60 min intensity, and kinetic energy (R , I_{60} , and E ; respectively; all about 10 %). The RCM-simulated spatial variability is somewhat lower compared to the area-average observations for the other characteristics (CV is 9 % for R , 8 % for I_{60} , and 18 % for event rainfall erosivity index (EI_{60} for the RCM simulations whereas these are 12 %, 12 %, and 29 %, respectively, for the area-average observations). CV) and significantly larger for the number of heavy events per season (N_{se}) and seasonal totals due to heavy events (S_{se}) is significantly higher in most of the RCM simulations (by almost as much as three times for N_{se} in several RCA4 simulations). Only for RACMO2 and RACMO22E simulations do CVs for N_{se} and S_{se} correspond well with the area-average observations (CV of about 25 and 30 % for N_{se} and S_{se} , respectively).

30 4.3 Quantile ratios (rt_p)

Figure 4 gives the quantile ratios (rt_p) for the RCM simulations and the area-average observations. For the latter, only the average value (from the 12.5, 25, and 50 km neighbourhoods) and envelope representing the maximum 5th-95th quantile range for all neighbourhoods is are shown (for details, see Sect. 4.1 and Fig. 2).

The correspondence between simulated and area-average event depths (D) is best for events with large D . ~~Some of the RCM simulations underestimate depths (D) for events with low D (which results in 7 % underestimation on average of D for the 0.05 quantile in the RCM simulations).~~ For most of the RCA4 runs, the quantile ratio rt_p does not depend on event depth (D). That is also the case for area-average observations.

5 For the longest events, the RCM-simulated event duration (T) corresponds relatively well with the area-average ~~and at-site~~ observations. However, shortest durations (T) are greatly overestimated (by 1.5 to 3.1 times; i.e. 2.3 times in the RCM simulations on average compared to the area-average characteristics). Only the event duration (T) in ~~the H5_ARPEGE~~ matches that of the area-average observations for the whole range of event durations.

The difference between ~~areal (RCM simulations as well as RCM-simulated and~~ area-average ~~observations) and at-site~~ rain-
10 fall rate (R) grows with increasing quantile. Stronger underestimation of largest rainfall rates (R) is related to significant overestimation of shortest durations (T). Moreover, underestimation of the maximum 60 min intensities (I_{60}) is greater for larger values –

~~Event rainfall energy (E) is related to the values for event depth (D) and duration (T). The overestimation of duration (T) for short events partly compensates for the underestimation of small depths (D), and that results in 15 % underestimation of~~
15 ~~the for most of the RCM simulations. The event~~ rainfall energy (E) ~~in the RCM simulations for low quantiles. As quantile increases the differences increase as well. Due to good correspondence between simulated and observed area-average largest event depths (D), however, the underestimation of E is smaller for the highest quantiles as well as the event rainfall erosivity index (EI_{60}) are considerably underestimated.~~

4.4 Histogram ratios (rt_f)

20 Differences in ~~distribution distributions~~ of rainfall event characteristics ~~values~~ between the RCM simulations and ~~the at-site observations are described~~ observations are characterized by histogram ratio rt_f (Fig. 5).

Considerably higher numbers of events with smaller depths (D) in the RCM simulations compared to the at-site observations are expected, partly due to the definition of a rainfall event (minimum values of D in the RCM simulations are between 7 and 11.5 mm). ~~Approximately 2.5 % of all considered events for at-site observations have~~ The proportion of events with
25 (D) smaller than 13 mm, while is 22–29 % for area-average observations and ~~the three spatial resolutions considered the proportion of such events is 22–29~~ 15–54 %. ~~For for~~ the ensemble of RCM simulations, ~~this range takes in 15–54 % of events~~. Extreme heavy events (with depths exceeding 250 mm), which rarely occur at some stations, are not present in most of the RCM simulations (exceptions being for all HIRHAM5 runs, HadRM3Q16 driven by ERA40, and HadRM3 driven by HadCM3).

30 Simulated numbers of events with short duration (~~T~~) are underestimated. Only 0.3–7.5 % (1.6 % on average) of events considered for the RCM simulations are shorter than 6 h, while for the area-average observations it is 9–13 % of events (~~15 % for the at-site observations~~).

Events with the smallest rainfall rates ($R < 0.5 \text{ mm h}^{-1}$) are more frequent in the RCM simulations (8–28 % of considered events) than in the area-average observations (5–8 %) ~~and at-site observations (7 %)~~. On the other hand, high rainfall rates

($R > 3 \text{ mm h}^{-1}$) are very rare for the RCM simulations (0.3–4 % of considered events), while for the area-average observations these represent from 8 to 15 % (and for at-site observations almost 19 %) of considered events.

Most of the simulated events (84–99 %) have maximum 60 min intensity (I_{60}) less than 6 mm h^{-1} . Among, while for the area-average and at-site observations, meanwhile, just observations it is only 60–72 % and 40 % of events, respectively, have $I_{60} < 6 \text{ mm h}^{-1}$. RCA4 simulations (50 km resolution) have absolute maximum values of I_{60} significantly lower compared to those of other RCM simulations (only around 11 mm h^{-1}).

Only 24 % of the observed at-site events considered have rainfall energy (E) below 2 MJ ha^{-1} , whereas for the area-average observations this figure is 51–58 % and for the RCM simulations it is 38–62 % (with mean 54 %) of events. The RCM simulations also have more events with low rainfall erosivity index (EI_{60}). For the RCM simulations, 68–92 % (with mean of 83 %) of events have $EI_{60} < 10 \text{ MJ mm ha}^{-1} \text{ h}^{-1}$, and for the area-average observations that range is 50–60 %. For the at-site observations, this low erosivity index occurs for only 26 % of events.

4.5 Altitude-dependence

Figure 6 shows the altitude-dependence of event characteristics for the RCM simulations and at-site observations (note that for the area-average observations the altitude-dependence has not been investigated due to an uneven spatial distribution and different numbers of stations in neighbourhoods). The altitude-dependence is expressed as the change in characteristics values of a characteristic per 100 m in elevation as estimated by a linear regression between altitude and the values of the rainfall event characteristics for a specific quantile. The linear regression is significant (with $p < 0.05$) for 78 % of all assessed quantiles for all characteristics and the at-site observations and for 68 % of those quantiles in the case of the RCM simulations.

Although the RCM simulations generally show a similar pattern of altitude-dependence as that for the at-site observations regarding most characteristics (with trends changes between -5 and $10 \text{ \%}/100 \text{ m}$ for all quantiles), several RCM simulations at 25 and 50 km resolutions show stronger altitude-dependence compared to at-site observations for high (event depth, duration, rainfall energy, and rainfall erosivity index) or low (rainfall rate and maximum 60 min intensity) quantiles of rainfall event characteristics. Two simulations with the highest horizontal resolution (RACMO22E and CLM) show different behaviour for greatest event depths (D) compared to those of other RCM simulations and at-site observations inasmuch as large D does not increase with altitude. These differences are nevertheless less than 5 %.

The linear regression is significant (with $p < 0.05$) for 78 % of all assessed quantiles for all characteristics and the at-site observations and for 68 % of those quantiles in the case of the RCM simulations. For RCM-simulated rainfall rates (R) and maximum 60 min intensities (I_{60}), however, the altitude-dependence is found to be significant much less frequently (58 and 51 % of cases) than for at-site observations (100 and 95 %, respectively). The number of significant regressions was also considerably smaller for the RCA4 runs with 50 km resolution.

Number of heavy events per season (N_{se}) and seasonal totals due to heavy events (S_{se}) strongly depend on altitude in the RCM simulations (not shown). Simulated N_{se} increase with altitude, with a slope coefficient β 1.8–7.7 times greater than those for at-site observations. A similar situation is found for S_{se} , with β 1.1–5.9 times greater. These steeper slope coefficients β make altitude-dependence of seasonal characteristics unrealistic compared to at-site observations for a large part of the

RCM simulations. Only two RCM simulations with the higher spatial resolution (CLM with 11.7 and 13.9 %/100 m, and RACMO22E with 15 and 21 %/100 m) represent the altitude-dependence of N_{se} and S_{se} for the Czech Republic adequately (~~trends-increases~~ for at-site observations are 8.4 and 13.4 %/100 m, respectively).

5 Discussion

5.1 Definition and characteristics of rainfall events

Heavy rainfall event characteristics were assessed in an ensemble of 23 RCM simulations. Events were identified while considering 6 h minimum inter-event time (MIT), 0.1 mm h⁻¹ fixed wet-hour threshold, and minimum total event depth derived for each RCM simulation as event depth with the same exceedance probability as for the 12.7 mm depth in the observed at-site rainfall events. ~~Setting the minimum event depth to the fixed value of 12.7 mm led to results generally similar to those presented in Sect. 4. On the other hand, setting the wet-hour threshold using quantile matching (i.e. in general to lower than 0.1 mm) resulted in excessive prolongation of rainfall events in some RCM simulations and distortion in the distributions of other event characteristics (15 %).~~

~~While the~~

~~While the same~~ 6 h MIT was used here for the ~~sake of consistency with the definition in other studies (e.g. Agnese et al., 2006; Murakami, 2006; Fiener et al., 2013; Hanel et al., 2016) and given by the USLE definition of events in the observed and simulated data in order to provide comparable event characteristics and to be consistent with other studies (e.g. Agnese et al., 2006; Murakami, 2006; Fiener et al., 2013; Hanel et al., 2016a) and methods (e.g. the USLE), the optimal MIT estimated by Hanel and Máca (2014) for the Czech Republic was considerably larger (426–2055 min, 763 min on average). Larger values of optimal MIT had been reported also by Dunkerley (2008b). ~~To explore~~ The evaluation of the optimal MIT for the RCM simulations, ~~we used the same procedure as considered by Hanel and Máca (2014) and which is based on the coefficient of variation (CV) of the inter-event times (Restrepo-Posada and Eagleson, 1982). Optimal MIT averaged across grid boxes for the RCM simulations varied led to average MIT varying~~ from 7 h (RCA4_NorESM1-M) to 27 h (HadRM3Q3 SUBSCRIPTNBHHadCM3adCM3), with an average value of ≈ 13 h. ~~Differences in~~ for an ensemble of RCMs. Also the optimal MIT ~~between varied considerably among the~~ grid boxes for ~~the individual RCM simulations were large, ranging~~ from 4 h for RCA4_CM5A-MR (optimal MIT in the range of 8–11 h) to more than 24 h for H5_ARPEGE (14–41 h). ~~The spatial variability was greatest for the three RCM simulations with the highest optimal MIT: HadRM3Q3_HadCM3, HadRM3Q3_ERA40, and H5_ARPEGE. Because MIT value strongly influences the values of event characteristics (e.g. higher MIT leads to a smaller number of events, consequently with larger duration and event depths; Hanel and Máca, 2014), the evaluation of event characteristics would not be feasible using estimated, highly variable MITs.~~ each RCM simulation.~~

5.2 Effect of areal averaging

~~The areal-averaging effect was considered when comparing at-site observed and RCM-simulated event characteristics. Observed area-average rainfall event characteristics were analysed for an extended period (1961–2009) in three spatial resolutions (12.5, 25, and 50 km) corresponding to the resolutions of the RCMs.~~

Estimates ~~as to~~ of the effect of areal averaging are influenced by several sources of uncertainties (Svensson and Jones, 2010), in particular by spatial variability and coverage of rain gauges. Because it is obvious that a sufficient number of stations must be available in order to provide a reliable estimate of the areal-averaging effect, we assessed the effect of the number of stations considered in the areal averaging on the estimated rt_m ratio using a dense rain gauge network for Prague (22 stations, 500 km²). The assessment was based on repetitive estimation of rt_m from resampled data with the number of stations used for areal averaging ranging from 2 to 22.

The number of stations included into the calculation of the areal average influenced most of the estimated event characteristics. Mean event depths (D) were least affected by the number of stations compared to other characteristics (with rt_m decreasing with the number of stations from -12 to -15 % of the at-site value). Event duration (T) was slightly increasing with the number of stations involved (from -5.6 to 4.3 %). Behaviour of D and T was reflected in the event mean rainfall rate (R), which was continually decreasing with the rising number of stations from -17 to -39 %. As a consequence, the ratios for maximum 60 min intensity (I_{60} ; -17 to -33 %), event rainfall energy (E ; -18 to -26 %), and event rainfall erosivity index (EI_{60} ; -36 to -59 %) were decreasing with the number of stations as well. The largest differences in ratios were observed between areal averages estimated from a small number of stations (typically fewer than 6). This finding is in agreement with Allen and DeGaetano (2005), who reported that areal reduction factors are not substantially influenced by the number of stations involved when derived from 10 or more stations. Observed area-average rainfall event characteristics for the study area (the Czech Republic) can therefore be partly affected by insufficient number of stations for ~~resolution~~ resolutions finer than 50 km (below 3 stations per neighbourhood).

Several conclusions can be drawn from the comparison of area-average and at-site characteristics in general:

- More heavy rainfall events are identified in area-average observations while the area-average seasonal total precipitation due to heavy events corresponds well with that from the at-site observations.
- Area-average event characteristic values are on average lower than are those for at-site observed characteristics, except that area-average event duration is longer for the shortest events and rainfall rate is comparable for events with low rates.
- For most of the rainfall event characteristics, the difference between the area-average and at-site observations grows with increasing non-exceedance probability (the exception being event depth, for which the difference is comparable across the whole distribution). ~~Many other studies~~ These findings complement other studies using areal reduction factors that point out larger differences between area-average and at-site rainfall for more extreme rainfall events maxima for longer return periods (e.g. Skaugen, 1997; Asquith and Famiglietti, 2000; Allen and DeGaetano, 2005).
- Considerably fewer events with high maximum 60 min rainfall intensity (I_{60}) and more events with low I_{60} occur in area-average observations than in at-site observations.

- The effect of areal averaging (lower values of characteristics with larger area, except for event duration) is generally in agreement with the review published by Svensson and Jones (2010) and the analysis of Eggert et al. (2015), who have shown (for radar data) a more pronounced decrease for more extreme convective precipitation intensity with coarser spatial and larger temporal resolution ~~derived from radar data~~. However, the estimated areal-averaging effect was not much different for the considered area sizes, and especially with respect to its great spatial variability. This might be a consequence of a small number of stations being available for estimation at finer spatial scales.

5.3 RCM-simulated rainfall event characteristics

Differences between the RCM-simulated and at-site observed characteristics are in general considerably larger than are those between the at-site and area-average observations, i.e. these differences are dominated by the RCMs' bias rather than the areal-averaging effect.

~~The ensemble-average number of heavy rainfall events is larger by 1.5 events (16 %) per season than for area-average observations, and the ensemble average of seasonal total precipitation due to heavy events is larger by 23 mm(11 %).~~

Although the RCM-simulated number of heavy events and seasonal total precipitation due to heavy events averaged across the Czech Republic correspond relatively well with the area-average observations (they are only slightly larger), large differences between individual grid boxes may be found (especially ~~due to elevation~~ in areas with complex orography). Generally good simulation of extremes (mean annual maxima, 20-year return values) in total precipitation amounts (from both convective and stratiform daily precipitation data together) ~~were also reported~~ was reported earlier for the Czech Republic by Kyselý et al. (2016).

~~Simulated event depths (D) are comparable with the area-average observations, with depths of extreme heavy rainfall events (with non-exceedance probability $p = 0.95$) corresponding best with the area-average observations. Because mean simulated (and area-average) event durations (T) are relatively long (> 16 h), the results are in general consistent with those of Hanel and Buishand (2010), who reported good representation of daily precipitation extremes for the area of the Netherlands even as hourly maxima tended to be too low. For the Czech Republic~~ On the other hand, Hanel and Buishand (2012) found larger negative bias in daily precipitation extremes for an ensemble of RCM simulations from the ENSEMBLES project in summer (by as much as 17 %), while the bias was significantly lower in spring and autumn. Hence, including May and September into rainfall data might reduce the bias, which is smaller in our study considering depths of individual heavy rainfall events.

Recent studies considering different spatial resolutions of RCM simulations suggest that hourly precipitation characteristics of extreme events are represented better in RCMs with higher spatial resolution (e.g. Ban et al., 2014; Chan et al., 2014b; Kendon et al., 2014). The better representation of hourly extremes is mainly due to the convection-resolving approach, however, because by increasing spatial resolution to approach the convection-permitting scale (about 4 km; Prein et al., 2015) it is possible to switch off most of the convection parameterizations (Fosser et al., 2015). All RCM simulations analysed in this paper rely on convection parameterization schemes, and the differences between RCM simulations conducted at different spatial resolutions are small and not systematic. ~~Also, Sunyer et al. (2016) suggest that differences between RCM simulations with convective parameterization due to spatial resolution are smaller are than differences due to RCM-GCM combinations~~

~~for precipitation extremes.~~ Therefore, characteristics of rainfall events for the RCM simulations with 50 km resolution (RCA4) also are not much different from ~~these~~ those for other RCM simulations. ~~Exceptions are~~ Exception is the highest maximum 60 min rainfall ~~intensities~~ intensity during an event (I_{60}), which ~~are~~ is underestimated more in RCA4 simulations compared to ~~these~~ that from other RCMs. ~~These results are in accordance with those of~~ This is a consequence of an insufficient resolution
5 for simulating sub-daily extremes as suggested by Sunyer et al. (2016), who concluded that the 50 km spatial resolution is not sufficient to reproduce hourly extreme precipitation even though the performance of the RCMs considering daily extremes seems not to depend on the spatial resolution.

The RCM-simulated maximum 60 min rainfall intensities (I_{60}) as well as the number of events with large rainfall rate (R) are significantly lower than for the observed data. This ~~is in accord with Kyselý et al. (2016), who concluded that intensity~~
10 ~~of RCM-simulated convective precipitation in summer is underestimated and that this underestimation is related to convective parameterization. Similar explanation for the underrepresentation of short-duration, high-intensity events in RCM simulations was given also by Kendon et al. (2012) may be explained by deficiencies in convective parameterization, as suggested by~~ Kendon et al. (2012) or Kyselý et al. (2016).

Overestimation of event duration (T) is a consequence of the well-known tendency of RCMs to produce too much persistent light rain and underestimate the number of dry days (e.g. Fowler et al., 2007; Boberg et al., 2009; Kendon et al., 2012).
15 This strongly impacts especially events with the shortest durations (T), which are severely overestimated in the RCM simulations. Large overestimation of short durations (T) then causes pronounced underestimation of larger rainfall rates (R). Fossier et al. (2015) reported the same issue of too-long events also for an RCM with higher resolution and most of the convective parameterizations turned off (COSMO-CLM, 2.8 km resolution).

It should be noted that when event duration (T) is corrected (i.e. the events are proportionally shortened according to
20 quantile ratio rt_p of event durations), mean rainfall rate (R) increases to values that are well comparable with the area-average observations. For instance, correcting the event durations (T) in the RACMO2_ECHAM5 simulation (corresponding best with the area-average event depths) results in an 80 % increase of mean R (mean characteristics are shown in Table 2). Shortening an event also increases the maximum 60 min intensity during an event (I_{60} ; by about 50 %), event rainfall energy (E ; by 10
25 %), and erosivity index (EI_{60} ; by 65 %), even though these values are still slightly below the area-average observations (ratios rt_m in Fig. 3 for corrected mean I_{60} , E , and EI_{60} would then be 0.46, 0.61, and 0.26, respectively).

Most analysed characteristics in most of the RCM simulations show a pattern of altitude-dependence similar to that for the at-site observations, and the differences in strength of the altitude-dependence for different quantiles of rainfall event characteristics are in general small (largest differences compared to at-site observations appear for simulations with the coarse
30 50 km resolution). The number of heavy events per season and seasonal total precipitation due to heavy events increase with altitude, and this dependence is captured better by RCM simulations with the higher spatial resolution. This could be expected due to better representation of orography as indicated by Rauscher et al. (2010) or Prein et al. (2016).

RCM simulations driven by ~~the ERA reanalyses~~ reanalysis do not in general show better results ~~compared to those from~~
35 ~~in simulating individual rainfall events compared to~~ the GCM-driven RCMs. That is in agreement with Hanel and Buishand (2010), who indicated that bias is largely due to the precipitation parameterization rather than the driving boundary condi-

tions. Although HadRM3 runs driven by the ERA40 reanalysis have event durations (T) considerably shorter than **these for** the GCM-driven simulations (i.e. they show greater similarity with observations), values for event depths (D) as well as other characteristics are generally lower in the ERA40-driven simulations. As a result, the distribution functions of the other event characteristics appear similar for the simulations driven by ERA40 as for those driven by GCMs, with larger differences occurring mostly between the perturbed and unperturbed runs. RCA4 driven by ERA-INTERIM reanalysis remains approximately in the middle of the range of all RCA4 runs for all **event** characteristics and all assessed ratios. That is in line with the inter-comparison of RCA4 simulations according to monthly precipitation amounts as reported by Strandberg et al. (2014).

The results and discussion presented so far were focused on the assessment of RCM performance in simulating individual rainfall events over a relatively small domain – the Czech Republic. It should be noted that at present there is no available dataset allowing for assessment of RCM performance at hourly time-scale over substantially larger domains or even whole Europe. However, while the bias in the RCM simulations is known to vary regionally, a number of findings can probably be transferred to other locations. This includes in particular the results concerning the effect of area averaging on the rainfall event characteristics but also the general deficiencies in the simulated event characteristics, such as strong underestimation of event rainfall rates, maxima and erosivity indices, overestimation of event duration, and dependence of the biases on the exceedance probability of event characteristics for event duration, rainfall rate and maxima.

The bias in temporal structure of sub-daily rainfall, revealed in this study, impairs in practice the use of simulated sub-daily rainfall in hydrological applications even after standard bias correction (e.g. quantile mapping), correcting the distribution of rainfall at sub-daily time scales. It was shown in several studies that despite the correspondence of the distribution at the corrected scale, the resulting simulated hydrological response may be severely biased even for daily data (e.g. Teng et al., 2015; Hanel et al., 2016b). This effect is expected to be even more pronounced in the case of sub-daily data, since the biases are larger. Therefore, unless advanced methods allowing for correction in the temporal structure of rainfall are considered, we discourage from application of bias correction methods for sub-daily RCM simulations and suggest applications of different approaches, e.g. delta change perturbations as presented recently by Sørup et al. (2016).

6 Conclusions

This study presents a methodology for analysis of precipitation characteristics in RCM simulations from an event-based perspective. Individual rainfall events **and their characteristics** are important with respect to many hydrological applications **and rainfall impact assessment studies**. Although it is generally not expected that the current RCMs would simulate sub-daily variability and rainfall event characteristics properly (e.g. Kendon et al., 2014; Westra et al., 2014), characterization of the biases can be useful for studies using simulated sub-daily rainfall data and also for the development of climate models, including research concerning their parameterizations, which is still very pertinent (e.g. Grell and Freitas, 2014) despite the increasing availability of convection-permitting RCM simulations (Prein et al., 2015). **The proposed methods allow for assessment of rainfall event characteristics in observed and RCM-simulated data and can be easily applied to other regions for which sub-hourly rainfall data are available.**

The results suggest that representation of individual rainfall events in the RCM simulations suffers from several deficiencies which have been only partly discussed in previous studies dealing with precipitation characteristics and extremes. The most important findings are summarized as follows:

- 5 • Differences between RCM-simulated and at-site observed rainfall event characteristics are dominated by the ~~bias~~ biases of the climate models rather than the areal-averaging effect.
- The RCMs on average represent the number of heavy rainfall events ~~and~~ seasonal total precipitation due to heavy events and event depths relatively well, ~~except that grid boxes at the highest altitudes produce large overestimation for some RCM simulations (in general, slightly higher numbers of events for most of the RCM simulations; however, the number of heavy events~~ as well as ~~a good representation of seasonal total precipitation for an ensemble of RCMs, despite larger differences for different RCM simulations)~~ the corresponding seasonal totals are overestimated at higher-elevated grid boxes.
- 10 • Simulated event ~~depths correspond relatively well with the area-average observations, while event~~ durations are overestimated. ~~Other characteristics (~~ while the event mean rainfall rate, maximum 60 min rainfall intensity, and indicators of rainfall event erosivity ~~)~~ are significantly underestimated.
- 15 • The underestimation is larger for larger rainfall rates and maximum 60 min rainfall intensities during an event. These characteristics are underestimated most for extreme heavy events.
- The largest deficiencies are found for events with short duration, which are longer in the RCM simulations compared to the area-average observations. Therefore, the numbers of events with shortest duration (below 10 h) ~~also are~~ also much lower in the RCM data. Overestimation of event durations then causes underestimation of rainfall rates and partly
- 20 • The increase of number of heavy rainfall events and seasonal total precipitation due to heavy events with altitude is considerably overestimated in all RCM simulations except those with the highest spatial resolution.

The limitations in RCM-simulated rainfall event characteristics should be taken into consideration when applying their outputs in hydrological studies and climate change assessments.

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Table 1. RCM simulations analysed.

RCM (reference) – Institution producing the model output			
Acronym	Driven by	Horizontal resolution	Number of gridboxes
CLM 2.4.11 (Böhm et al., 2006; Lautenschlager et al., 2009) – Max Planck Institute for Meteorology (MPI), Germany			
CLM	ECHAM5/MPIOM	22 km (0.2°)	301
HadRM3.0 (Collins et al., 2011) – Met Office Hadley Centre (MOHC), UK			
HadRM3Q0_ERA40	ERA40	25 km (0.22°)	173
HadRM3Q3_ERA40	ERA40		
HadRM3Q16_ERA40	ERA40		
HadRM3Q0_HadCM3	HadCM3Q0		
HadRM3Q3_HadCM3	HadCM3Q3		
HadRM3Q16_HadCM3	HadCM3Q16		
HIRHAM5 (Christensen et al., 2007) – Danish Meteorological Institute (DMI)			
H5_ARPEGE	ARPEGE	25 km (0.22°)	173
H5_BCM	BCM		
H5_ECHAM5	ECHAM5-r3		
RACMO2.1 (van Meijgaard et al., 2008) – Royal Netherlands Meteorological Institute (KNMI)			
RACMO2_ECHAM5	ECHAM5-r3	25 km (0.22°)	173
RACMO2_MIROC	MIROC3.2		
RACMO22E (van Meijgaard et al., 2012) – Royal Netherlands Meteorological Institute (KNMI)			
RACMO22E	ICHEC-EC-EARTH	12.5 km (0.11°)	607
RCA4.0 (Kupiainen et al., 2011; Samuelsson et al., 2011) – Swedish Meteorological and Hydrological Institute (SMHI)			
RCA4_ERAIN	ERA-INTERIM	50 km (0.44°)	52
RCA4_CanESM2	CCCma-CanESM2		
RCA4_CM5A-MR	IPSL-CM5A-MR		
RCA4_CNRM-CM5	CNRM-CM5		
RCA4_EC-EARTH	ICHEC-EC-EARTH		
RCA4_ESM2M	NOAA-GFDL-ESM2M		
RCA4_ESM-LR	MPI-ESM-LR		
RCA4_HadGEM2-ES	MOHC-HadGEM2-ES		
RCA4_MIROC5	MIROC5		
RCA4_NorESM1-M	NCC-NorESM1-M		

Table 2. Seasonal number of heavy rainfall events (N_{se} [–]), seasonal total precipitation due to heavy events (S_{se} [mm]), and mean rainfall event characteristics (depth D [mm], duration T [mm], mean rainfall rate R [mm h^{−1}], maximum 60 min intensity I_{60} [mm h^{−1}], rainfall energy E [MJ ha^{−1}], and rainfall erosivity index EI_{60} [MJ mm ha^{−1} h^{−1}]) for the 1981–2000 period in the observed data (top 4 rows) and the RCM simulations.

Acronym	N_{se}	S_{se}	D	T	R	I_{60}	E	EI_{60}
At-site observations average	7.62	194.7	25.0	19.7	2.37	9.38	3.66	48.75
Area-average observations								
12.5 km	9.41	205.6	21.4	16.2	2.14	7.20	2.92	28.88
25 km	9.00	197.9	21.6	17.1	2.02	6.82	2.89	26.16
50 km	9.66	198.8	20.2	18.1	1.73	5.68	2.56	18.77
Summary of RCM simulations								
RCMs average	10.82	223.4	20.0	23.2	1.04	2.93	2.02	7.88
12.5 km res. RCM	11.20	212.5	18.8	25.9	0.86	3.00	1.90	7.96
25 km res. RCMs	10.54	215.2	19.8	22.3	1.08	3.12	2.04	9.08
50 km res. RCMs	11.08	235.0	20.5	23.9	1.02	2.60	2.01	5.97
RCM simulations								
CLM	10.84	208.9	19.2	22.8	1.06	3.91	2.09	13.58
HadRM3Q0_ERA40	11.83	239.2	19.6	20.6	1.19	3.74	2.11	12.28
HadRM3Q3_ERA40	10.05	169.5	16.5	18.8	1.00	2.90	1.70	6.99
HadRM3Q16_ERA40	11.40	226.7	19.1	21.5	1.08	3.21	1.98	9.56
HadRM3Q0_HadCM3	11.33	278.3	23.9	23.2	1.28	4.20	2.62	16.90
HadRM3Q3_HadCM3	10.51	209.0	19.5	21.6	1.04	3.01	2.01	8.56
HadRM3Q16_HadCM3	10.31	231.7	21.6	23.2	1.11	3.48	2.27	11.84
H5_ARPEGE	7.61	132.7	16.9	17.4	1.19	2.83	1.70	5.67
H5_BCM	12.70	246.6	18.5	20.5	1.08	2.51	1.83	5.27
H5_ECHAM5	11.11	224.7	19.0	20.5	1.13	2.91	1.92	6.54
RACMO2_ECHAM5	9.42	191.0	20.2	26.6	0.91	2.81	2.02	7.69
RACMO2_MIROC	9.67	217.8	22.4	31.1	0.85	2.74	2.24	8.63
RACMO22E	11.20	212.5	18.8	25.9	0.86	3.00	1.90	7.96
RCA4_CanESM2	10.65	221.5	20.0	23.9	1.01	2.63	1.97	6.01
RCA4_CM5A-MR	11.14	219.4	19.2	22.7	1.02	2.53	1.89	5.46
RCA4_CNRM-CM5	12.38	289.2	22.5	25.0	1.07	2.77	2.23	6.94
RCA4_EC-EARTH	11.11	249.7	21.7	26.4	0.95	2.44	2.11	5.86
RCA4_ERAINI	10.20	208.1	19.9	23.0	1.03	2.67	1.97	6.04
RCA4_ESM2M	12.08	275.6	22.2	26.1	0.99	2.53	2.17	6.25
RCA4_ESM-LR	11.45	257.9	21.9	25.0	1.06	2.72	2.17	6.65
RCA4_HadGEM2-ES	9.93	173.3	16.8	21.6	0.93	2.35	1.62	4.35
RCA4_MIROC5	10.11	221.2	21.2	23.0	1.11	2.83	2.11	6.67
RCA4_NorESM1-M	11.76	233.8	19.2	21.9	1.03	2.57	1.89	5.41

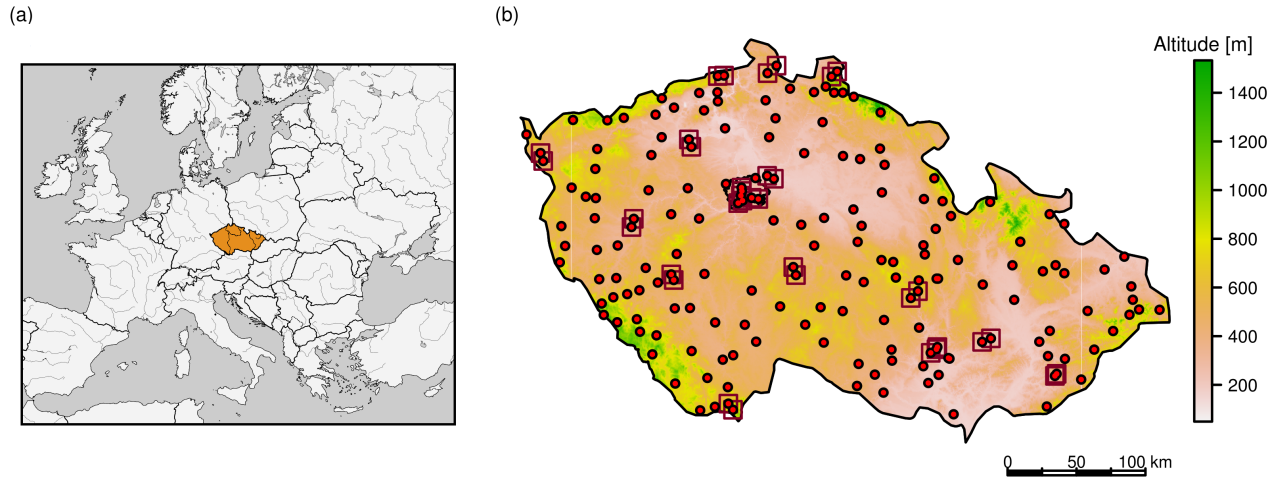


Figure 1. (a) Location of the Czech Republic in Central Europe. (b) Stations (dots) used for assessing the areal-averaging effect and evaluating the RCM simulations. Rectangles show considered (36) square neighbourhoods for assessing the areal-averaging effect for 12.5 km resolution. Altitude is indicated by colour.

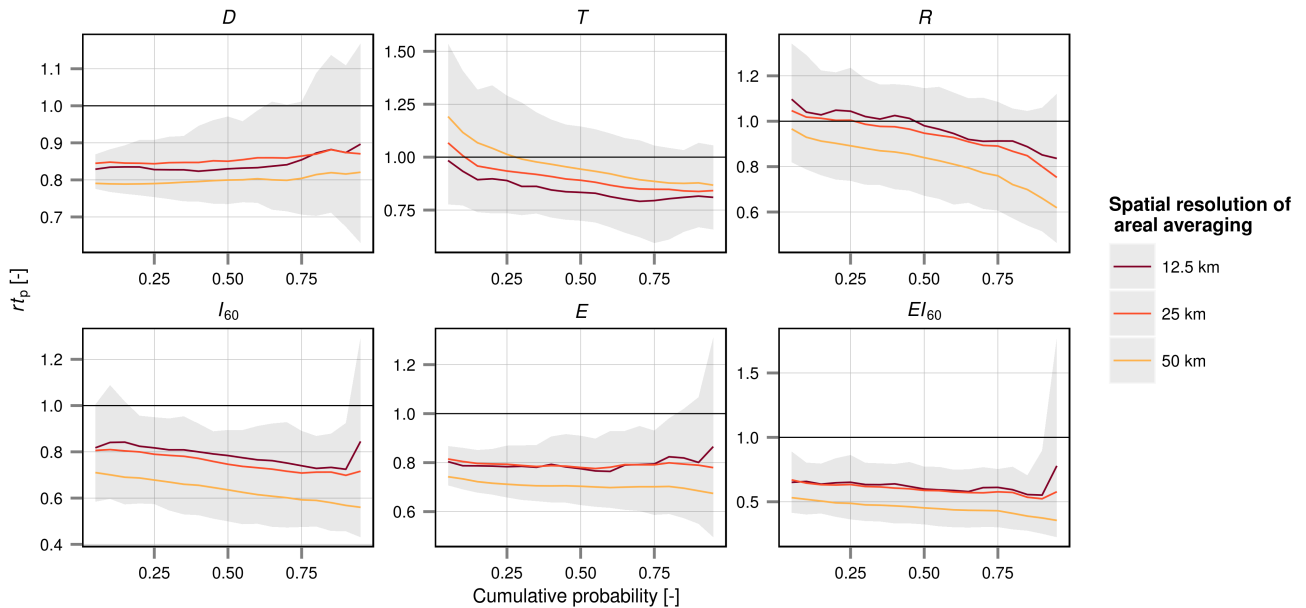


Figure 2. Quantile ratios rt_p for the distribution of the area-average and at-site rainfall event characteristics (D , T , R , I_{60} , E , EI_{60}). For each spatial resolution (12.5, 25, 50 km), the average from all neighbourhoods is indicated by solid line. Envelopes of rt_p for all neighbourhoods (grey areas) represent the maximum range between the 5th and 95th quantiles for the three considered spatial resolutions.

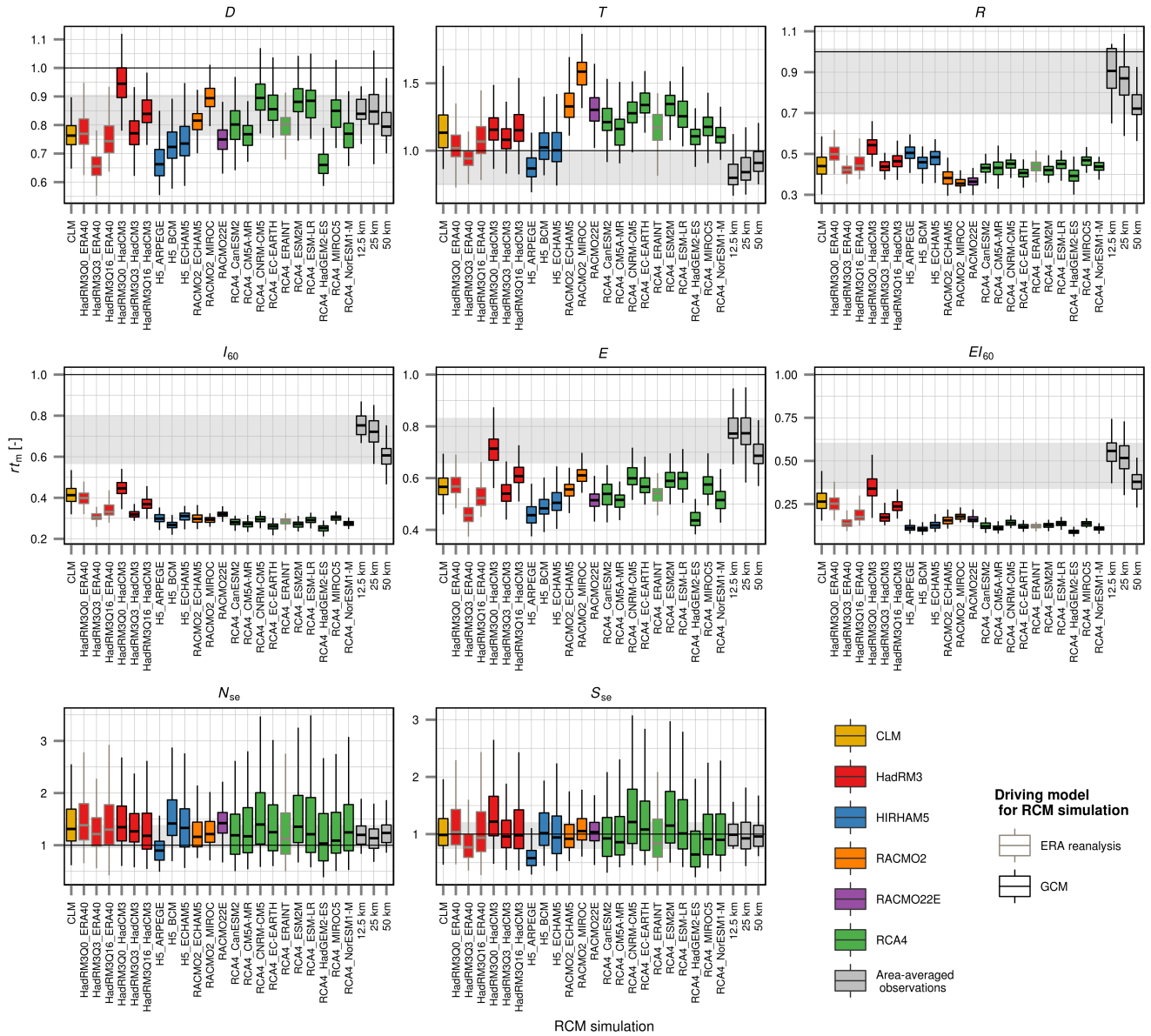


Figure 3. Ratios rt_m between areal (grid box or neighbourhood) and station average of mean (event and seasonal) characteristics for each RCM simulation and area-average observations (grey boxplots in the right part of each panel). Each boxplot corresponds to values for all grid boxes (neighbourhoods) over the Czech Republic. Grey areas indicate the range between the minimum 25th and maximum 75th quantiles of rt_m for observed data from all neighbourhoods.

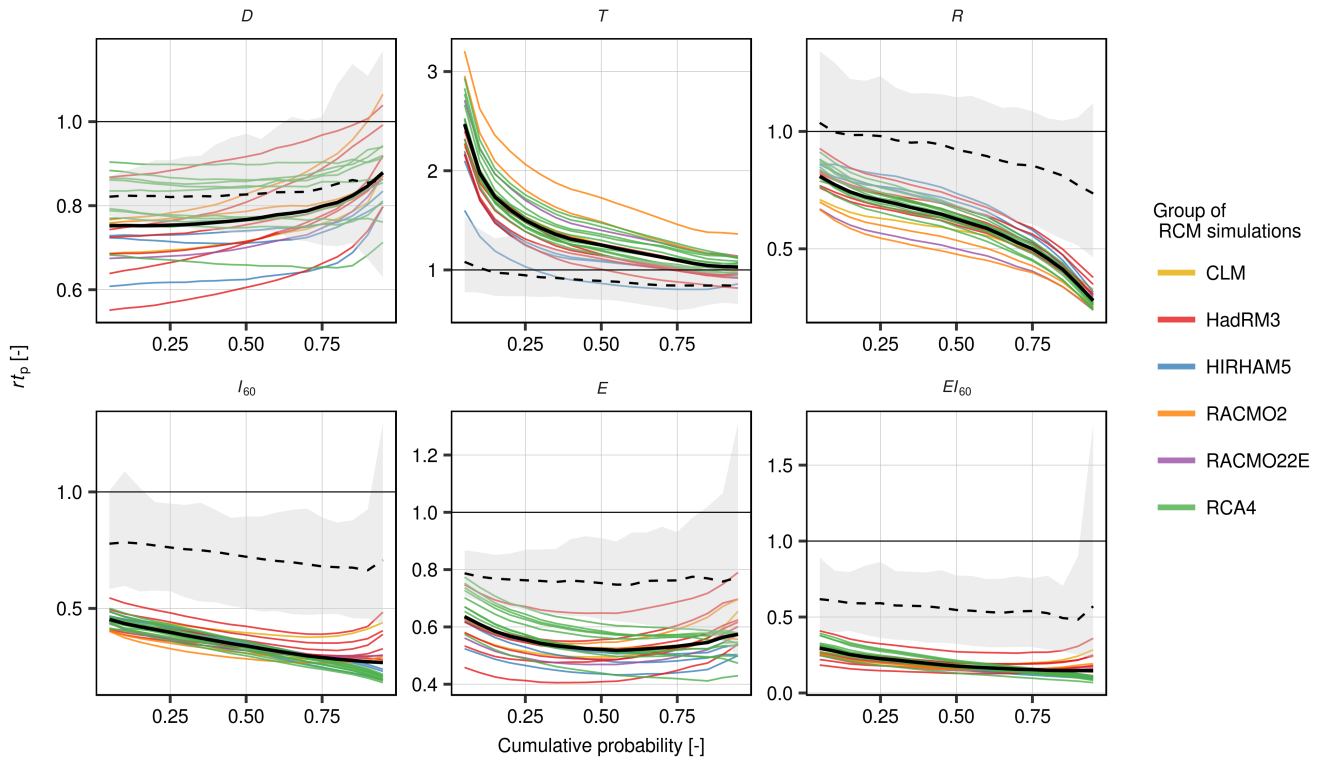


Figure 4. Area-average quantile ratios r_{t_p} for the event characteristics derived from RCM simulations. Bold black line shows average from all RCM simulations. Grey area corresponds to the 90 % envelope of the quantile ratios for the area-average observations, and broken line indicates the areal average.

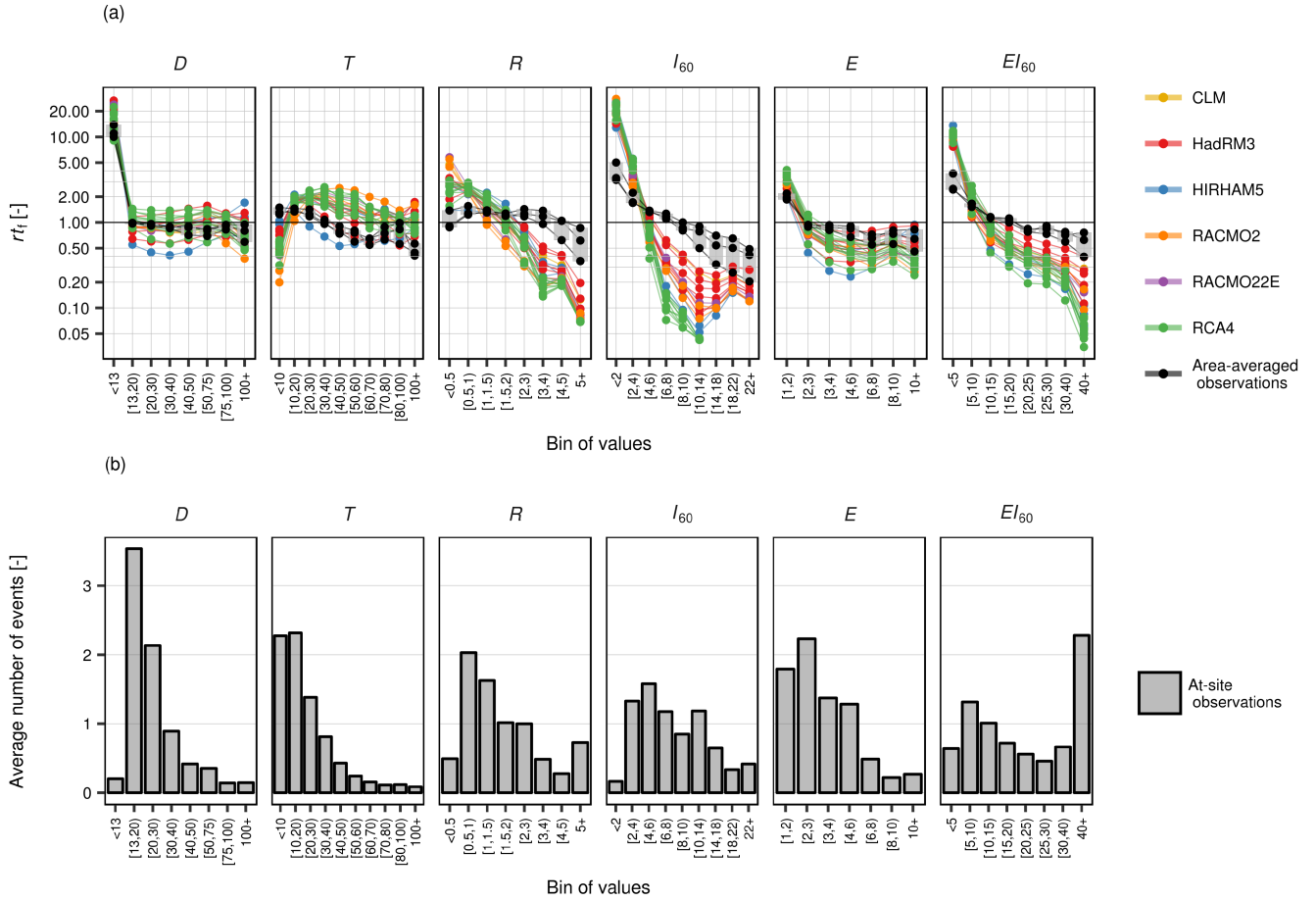


Figure 5. (a) Histogram ratios rt_f between areal and station average of frequencies of corresponding bins of the histograms of rainfall event characteristics. Frequencies of bins are averaged per individual season and grid box for the RCM simulations (or neighbourhoods for area-averaged observations). Grey bars highlight ranges between the 12.5, 25, and 50 km area-average observations (black dots). (b) Histograms of the number of at-site events averaged per individual season and individual station. Units of characteristics defining bins of values are: mm (D), h (T), mm h^{-1} (R , I_{60}), MJ ha^{-1} (E), and $\text{MJ mm ha}^{-1} \text{h}^{-1}$ (EI_{60}).

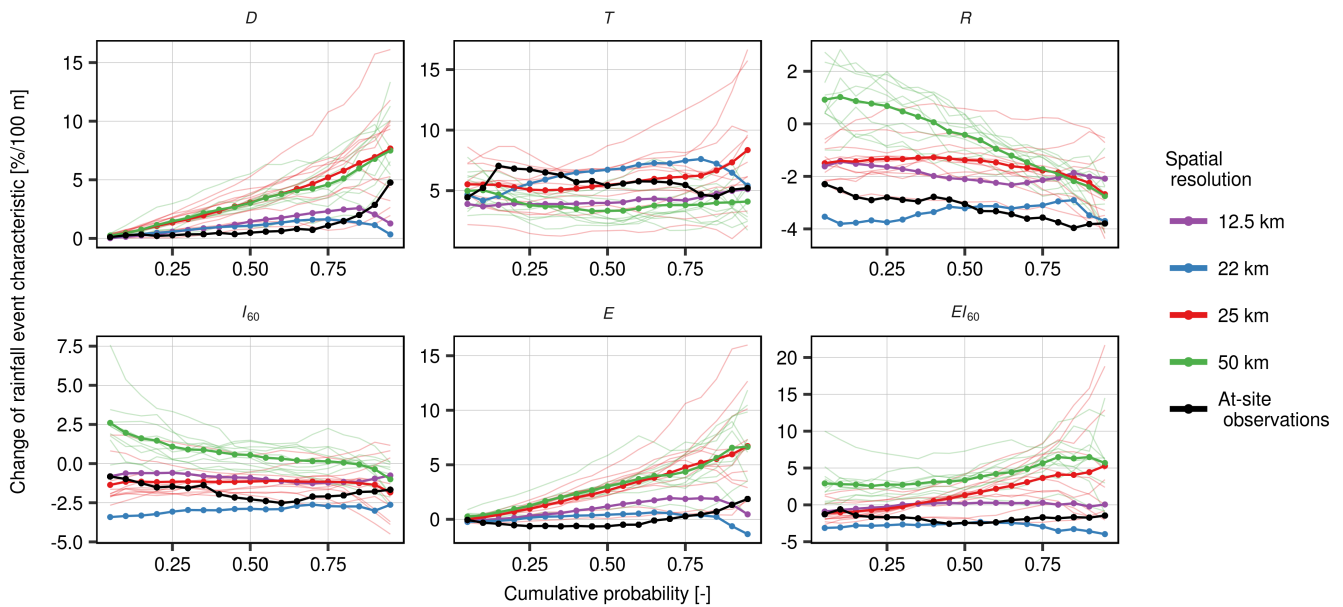


Figure 6. Dependence between-of rainfall event characteristics and-on altitude. Dependence is expressed by the change of characteristic per 100 m in elevation for the corresponding probability from the empirical distribution function of the event characteristics. Spatial resolution of the RCM simulations is indicated by colour (lines with points show RCM simulations average).